Hydrogen for Australia's future

A briefing paper for the COAG Energy Council

Prepared by the Hydrogen Strategy Group

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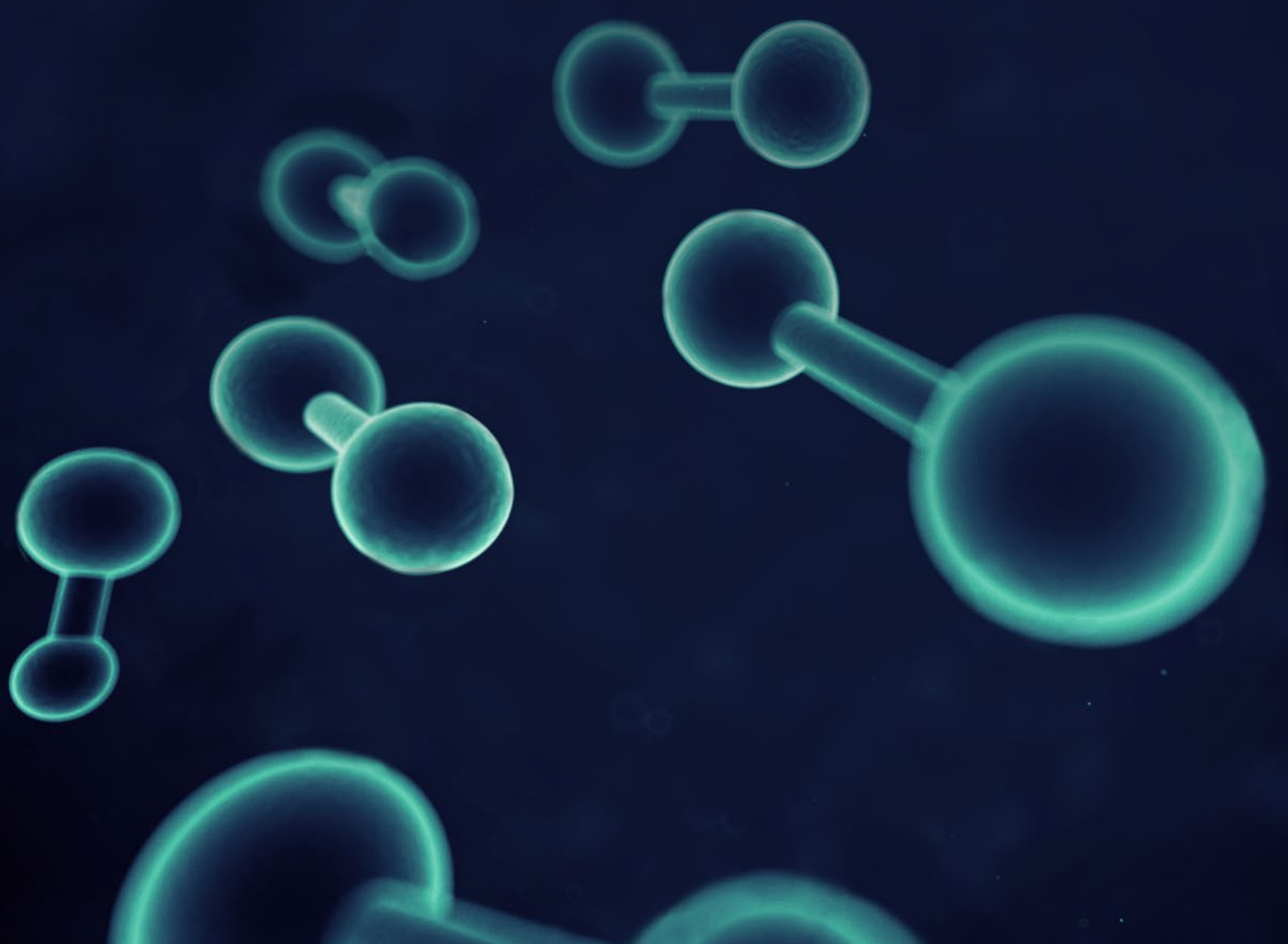

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Hydrogen Strategy Group Vision Statement

Our vision is a future in which hydrogen provides economic benefits to Australia through export revenue and new industries and jobs, supports the transition to low emissions energy across electricity, heating, transport and industry, improves energy system resilience and increases consumer choice.

The Key Opportunity

To capture the hydrogen export market and associated benefits in the domestic economy.

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10 August 2018

The Hon. Josh Frydenberg MP
Commonwealth Minister for Environment and Energy
and COAG Energy Council Ministers

Dear Ministers,

The long-held dream of meeting energy needs with clean hydrogen is becoming a reality. There are three drivers:

1. **Energy export.** Nations like Japan and South Korea that import most of their energy in the form of coal, oil and natural gas need cleaner energy to meet their CO_2 emissions reduction targets. Clean hydrogen is ideal. Japan has already declared it will be a large-scale hydrogen user. As yet, there are no large-scale exporters. This is a significant opportunity for Australia, given our ample renewable energy and convertible fossil-fuel reserves.
2. **Domestic economy.** Hydrogen can heat our buildings, power our vehicles and supply our industrial processes. These applications represent opportunities to expand manufacturing and generate spillover innovation and jobs while lowering our CO_2 emissions.
3. **Energy system resilience**. Hydrogen production from electricity and water is a flexible load that can respond rapidly to variations in electricity production and can contribute to frequency control in the electricity grid. Some of the hydrogen can be used, like a battery, to store electrical energy, while domestic utilisation of hydrogen will reduce reliance on imported fuels.

I ask myself "why now?" given that the idea of a hydrogen economy has been seriously and frequently proposed since 1972. The answer is Japan's commitment to be a large-scale enduring customer, and the hundredfold reduction in the price of solar electricity in the past four decades.

Safety is paramount. The benefits to our domestic economy will only be realised by a wholehearted commitment to safety in all aspects of operation. Hydrogen produced from fossil fuels (but without carbon capture and storage) has been used for many decades for fertiliser production and oil refining, and has an exemplary safety record. There is every reason to think this safety record can be preserved as we scale up the reach of hydrogen into buildings and vehicles, as long as we commit to safety first and foremost in all that we do.

Reducing the cost of producing hydrogen is the major challenge for Australia to position itself to be a major exporter of hydrogen, complementing our success in the LNG market. Japan has set targets for the landed import price in today's dollars of A$33/GJ in 2030 and A$22/GJ in the longer term. To reach these targets requires investing in research, development and deployment.

Industry is investing but is held back by the chicken-and-egg problem. Elements such as electricity generation, carbon sequestration, pipelines, electrolysers, refuelling stations and regulations depend on progress in the others. The federal, state and territory governments can provide the leadership to help these interdependent players make collective progress.

The Hydrogen Strategy Group was formed by experts who see the opportunities for hydrogen in our future economy, subject to development of the policies, technologies and infrastructure needed to safely and economically foster this new industry.

Ministers, I take this opportunity to thank you for inviting the Hydrogen Strategy Group to present this report.

Alan Finkel
Chair, Hydrogen Strategy Group

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Executive summary

A fuel for the 21st century

Like natural gas, hydrogen can be used to heat buildings and power vehicles. Unlike natural gas or petrol, when hydrogen is burned there are no CO_2 emissions. The only by-products are water vapour and heat.

Hydrogen is the most abundant element in the universe, not freely available as a gas on Earth but bound into many common substances including water and fossil fuels.

Hydrogen was first formally presented as a credible alternative energy source in the early 1970s but never proved competitive at scale as an energy source – until now. We find that the worldwide demand for hydrogen is set to increase substantially over coming decades, driven by Japan's decision to put imported hydrogen at the heart of its economy. Production costs are falling, technologies are progressing and the push for non-nuclear, low-emissions fuels is building momentum. We conclude that Australia is remarkably well-positioned to benefit from the growth of hydrogen industries and markets.

Exporting hydrogen

The most immediate economic opportunity for Australia is to establish itself as hydrogen supplier of choice to Japan and other nations such as South Korea that are hungry for hydrogen as a cost-effective route to reducing emissions.

Several nations, including Norway, Brunei and Saudi Arabia, are actively pursuing the global hydrogen supply market. Australia, however, has some key natural advantages as a supplier of hydrogen produced by the two commercially feasible low-emissions methods. Once produced, hydrogen can be exported as liquefied hydrogen (LH2) in the same way as liquefied natural gas (LNG), or chemically converted into another form such as ammonia.

Renewable hydrogen is produced by splitting water molecules into hydrogen and oxygen through a process called electrolysis, powered by solar, wind or hydro electricity. Australia has the abundant land area and renewable energy resources required to derive hydrogen by electrolysis at industrial scale. For a large-scale export industry, new dedicated solar and wind generators will be required.

Carbon capture and storage hydrogen (CCS hydrogen) can be produced from Australia's extensive coal and natural gas reserves, in particular our open-cut brown-coal mines. The processes to make hydrogen from fossil fuels all produce unwanted CO_2 emissions as a by-product but the impact can be mitigated by capturing and sequestering the carbon in underground storage sites.

Australia has the advantage of proven offshore sites suitable for the sequestration a large-scale CCS hydrogen industry will require. A Japanese-led consortium is testing the viability of this approach through a $500 million demonstration project launched in April 2018 to produce hydrogen from brown coal in Victoria's Latrobe Valley.

Access to the Japanese energy market is the prize for the nations now bidding to be global hydrogen suppliers. Japan, the world's third-largest economy by GDP, currently imports 94% of its energy as coal, oil and natural gas.

Japan does not have domestic access to low emissions resources at the scale required to replace these, and so its comprehensive multi-decade plan to transition to hydrogen spans both the take-up of hydrogen for domestic use and outreach to international partners as hydrogen producers and potential hydrogen technology customers. Similarly, South Korea imports 81% of its energy and has signalled its strong commitment to the uptake of hydrogen.

Australia is already a trusted energy supplier to Japan, which buys almost half of Australia's LNG exports, valued at A$23 billion in total in 2017. Our existing trade relationships and domestic expertise in LNG stand us in good stead to pursue a tandem export hydrogen industry. With the right policy settings, Australian hydrogen exports could contribute A$1.7 billion and provide 2,800 jobs by 2030.

Domestic economy

In the Australian domestic market, there are many opportunities to use hydrogen as an alternative to natural gas. Progress in hydrogen technologies will make these opportunities increasingly attractive over time.

The primary consideration in delivering hydrogen is attention to safety and community awareness. Like LNG, the use of hydrogen requires careful regulation. Hydrogen has been safely produced and used in large quantities in industry for many decades and is routinely transported in pipelines in Europe and the United States. With the right regulatory settings, confidence in the technology will grow as communities become accustomed to its use.

Hydrogen can be safely added to natural gas supplies at 10% by volume without changes to pipelines, appliances or regulations. Over time, and with modifications to the existing gas networks and appliances, hydrogen can completely replace natural gas for domestic cooking, heating and hot water. In the longer term, hydrogen can be used in high-temperature manufacturing processes such as in steel, fertiliser and cement production that currently have high CO_2 emissions.

The electrolysis units that produce hydrogen from electricity and water provide a fast responding load well-suited to following variable renewable electricity generation. As electrical loads, electrolysis units can be commanded to rapidly ramp up and down without consequence, thus they can contribute to frequency control services in the electricity grid. Once produced, stored hydrogen can be used in turbines or fuel cells to generate electricity. These capabilities will contribute to the resilience of the national electricity grid.

In the transport sector, accounting for 18% of Australia's emissions, hydrogen fuel cells are an alternative to batteries for powering electric motors. The Japanese government has set a target of 40,000 hydrogen fuel cell cars on the road by 2020. Mobility applications are already being explored in Australia, including hydrogen-powered cars, garbage trucks and forklifts. We anticipate future domestic demand for hydrogen-powered long-haul heavy transport such as buses, trucks, trains and ships.

Australia-wide benefits

The benefits of an Australian hydrogen production industry could be widely shared. Almost every state and territory has strong solar and wind potential to drive electrolysis. Tasmania has vast hydro-electric infrastructure. Victoria, Western Australia, South Australia, Queensland, the Northern Territory and New South Wales have carbon storage resources that could be used in the production of CCS hydrogen. South Australia and the Australian Capital Territory have hydrogen demonstration projects in the pipeline, supplied by ample renewable electricity generation.

Most of the major facilities and infrastructure will by necessity be located outside major cities, following the lead of the A$500 million hydrogen supply project in the Latrobe Valley. There are further electrolysis pilot projects planned near Port Lincoln in South Australia and in the Pilbara region of Western Australia, both of which will be used to produce ammonia for fertiliser production.

Hydrogen also has the potential to be an energy source in remote areas of Australia, such as mining sites, with fuel cells running on hydrogen produced on-site replacing diesel generators.

Next steps

The aim of this report is to flag the scope of Australia's hydrogen potential and frame discussions for a national strategy. Industry has signalled its intention to invest but recognises the important role of governments at all levels in reaching out to global partners and establishing the right policy settings at home.

As a critical first step, the development of an overarching national hydrogen strategy will identify in detail the necessary actions to capitalise on our prime position.

A national hydrogen strategy can define the role for government and industry in:

- International agreements and regulations, including shipping, to position Australia as the world's leading hydrogen exporter.
- Standards to ensure safety in all aspects of the hydrogen sector.
- Regulations to enable the addition of hydrogen to existing domestic gas supplies.
- Refuelling infrastructure and regulations for hydrogen vehicles.

We conclude that hydrogen has an important place in a carbon-constrained global economy and that Australia can profit by accelerating its uptake. The hydrogen market is ours to make.

1 Introduction

1.1 Why hydrogen?

From a consumer perspective, hydrogen is a gas much like natural gas that can be used to heat buildings and power vehicles.

From an environmental perspective, hydrogen is unique among liquid and gaseous fuels in that it emits absolutely no CO_2 emissions when burned.

From a scientific perspective, hydrogen is the simplest and most abundant element in the universe. As an atom, it consists of one electron and one proton. As a molecule (H_2), it is a colourless, odourless, non-toxic gas. It was first identified by British scientist Henry Cavendish in 1766, and later named by French chemist Antoine Lavoisier (from the Greek 'hydro' and 'genes', meaning 'born of water'). Cavendish was quick to grasp its energy potential, igniting it during a lecture to the Royal Society.[1]

From an energy perspective, hydrogen has two outstanding properties. First, it is an excellent carrier of energy, with each kilogram of hydrogen containing about 2.4 times as much energy as natural gas.[2] This energy can be released as heat through combustion, or as electricity using a fuel cell. In both cases the only other input needed is oxygen, and the only by-product is water. The chemical reaction is:

$$2H_2 + O_2 \rightarrow 2H_2O + \text{energy}$$

Second, hydrogen is a carbon-free energy carrier, with reactions such as that shown above producing no CO_2 or any other greenhouse gas. Using hydrogen in place of fossil fuels therefore offers a pathway to decarbonise energy systems. At a global level, replacing fossil fuel use with carbon-free hydrogen will significantly reduce greenhouse gas emissions, with estimated potential annual abatement of up to 6 billion tonnes of CO_2 by 2050.[3] (For comparison, the quantity of CO_2 emitted in 2017 was 32 billion tonnes.) At that scale, the hydrogen economy will be worth an estimated US2.5 trillion.[4]

The obstacle to realising hydrogen's clean energy potential is that on Earth it is virtually non-existent in its free form. Energy must be used to liberate it from the material forms in which it exists, such as water, biomass, minerals and fossil fuels.

The most common production methods are to split water molecules into hydrogen and oxygen using electricity, or through a thermochemical reaction using fossil fuels. The hydrogen is compressed for transmission to where it is needed while the oxygen is harmlessly released into the atmosphere. The energy to produce the hydrogen is subsequently released at the point of use. As such, hydrogen is technically an energy *carrier* rather than an energy *source*.

1 "Hydrogen", Encyclopaedia Britannica, accessed July 5, 2018, https://www.britannica.com/science/hydrogen
2 Based on lower heating value: "Fuels: higher and lower caloric value", The Engineering Toolbox, accessed July 5, 2018, https://www.engineeringtoolbox.com/fuels-higher-calorific-values-d_169.html
3 Hydrogen Council, *Hydrogen scaling up: A sustainable pathway for the global energy transition*, 2017.
4 Hydrogen Council, *Hydrogen scaling up*.

The hydrogen traditionally used as an industrial feedstock – in oil refining and the production of fertiliser and plastics – is made using fossil fuels. In future, for hydrogen to decarbonise energy systems and industrial processes, it must be produced using renewable electricity or from fossil fuels with carbon capture and storage (CCS).

This briefing paper only considers hydrogen produced with zero or very low CO_2 emissions.

There are three key opportunities hydrogen provides Australia (Figure 1).

1.1.1 Hydrogen for export

Due to its potential for decarbonising energy systems, many countries around the world are investing to develop hydrogen energy value chains. Japan and South Korea, which depend heavily on imported fossil-fuel energy, are seeking to replace those fuels with imported hydrogen. Their emerging import demand equates to a large export opportunity for Australia. We have an abundance of low-cost renewable solar and wind energy, and an abundance of low-cost brown coal alongside CCS sites. Coupled with our existing expertise in natural gas infrastructure and shipping, Australia is well-positioned to take a lead in the emerging hydrogen export market.

Figure 1: Key opportunities for Australia through developing large-scale hydrogen production capability.

1.1.2 Hydrogen for the domestic economy

Hydrogen has a range of uses for the domestic economy. It can be used instead of natural gas to heat buildings, for cooking and to provide hot water, in most cases using existing gas pipelines. It can be used for high-temperature industrial processes, such as making alumina. It can be used for transport, with the earliest large-scale application being for heavy vehicles. It can be used as a chemical feedstock for existing and new industries.

These applications represent opportunities to expand manufacturing, develop new industries and generate spillover innovation and jobs while transitioning to a low-carbon economy.

1.1.3 Hydrogen for energy system resilience

An industry producing clean hydrogen for export and domestic use can support electricity grid security and reliability in three major ways. First, electrolysers can rapidly respond to variations in generation output, acting as flexible loads consuming excess renewable energy when it is available and deferring to other loads when generation output is low. Second, electrolysers as large electrical loads can be rapidly ramped up and down to contribute to frequency control services on the national electricity grid. Third, hydrogen can be stored and used to generate electricity when needed.

Hydrogen will also contribute to the resilience of the broader energy system by diversifying the energy mix. In particular, using hydrogen to power a significant part the national road fleet can reduce reliance on imported liquid fuel and mitigate the risk of supply disruptions.

1.2 Why now?

Interest in the transformative power of hydrogen goes back half a century. In 1972, John Bockris, then a professor at Flinders University in South Australia, outlined the potential of a 'hydrogen economy' in *Science* magazine.[5]

Since then, research and commercial activity aimed at realising that vision has waxed and waned. In Australia, reports such as the *National Hydrogen Study* (2003)[6] and *Australian Hydrogen Activity* (2005)[7] highlighted opportunities and research activities. The COAG-sponsored *Hydrogen Technology Roadmap*[8] provided an updated overview in 2008, with particular focus on fuel cell technologies.

Now the emergence of countries determined to decarbonise their economies using hydrogen but lacking the low-emissions natural resources to make it have upped the stakes. The three linked factors of decarbonisation drivers, emerging export markets and falling renewable electricity costs mean the narrative is no longer about *research opportunity* but *market activation*.

5 John Bockris, "A hydrogen economy", *Science*, vol. 176, issue 4041, 23 June 1972.
6 Department of Industry, Tourism and Resources, *National Hydrogen Study*, 2003.
7 Department of Resources, Energy and Tourism, *Australian Hydrogen Activity*, 2005.
8 Department of Resources, Energy and Tourism, *Australian Technology Roadmap: Enhancing Australia's economic prosperity*, 2008.

Since 2015, 194 countries have agreed to reduce their greenhouse gas emissions.[9] Governments are developing and implementing policies to meet their targets. Australia is committed to having a long-term emissions reduction strategy by 2020.[10]

Japan, South Korea, Britain, France, Germany, China and the United States have all made significant progress on policies that extend beyond reducing emissions from electricity generation to include all aspects of energy transmission, storage and use. Hydrogen is recognised as a nearly ideal energy carrier for these measures. Japan's 2017 *Basic Hydrogen Strategy*, for example, embraces all aspects of hydrogen import, utilisation and spin-off industries.[11] (See box below.)

The dramatic fall in the cost of solar and wind electricity generation has outstripped even the most optimistic predictions of a few years ago.[12] This opens the possibility to make hydrogen cost-effectively for the wholesale electricity and gas markets. The electrolysers that produce hydrogen from water and electricity have yet to be manufactured at scale and right now add considerably to the cost of producing hydrogen, however it is expected their capital and operating costs will fall substantially as the hydrogen industry develops.

9 "COP21", United Nations Framework Convention on Climate Change, accessed July 4, 2018, https://unfccc.int/process-and-meetings/conferences/past-conferences/paris-climate-change-conference-november-2015/cop-21
10 Department of the Environment and Energy, *2017 Review of Climate Change Policies*, 2017.
11 Ministerial Council on Renewable Energy, *Hydrogen and Related Issues, Basic Hydrogen Strategy*, 2017.
12 International Energy Agency, *Renewables 2017: Analysis and Forecasts to 2022*, 2017.
13 "Basic hydrogen strategy key points", Ministry of Economy, Trade and Industry, accessed July 5, http://www.meti.go.jp/english/press/2017/pdf/1226_003a.pdf
14 Based on a conversion of ¥1 to A$0.012.
15 "South Korea: energy imports", The Global Economy, accessed July 12, 2018, https://www.theglobaleconomy.com/South-Korea/Energy_imports/
16 "Republic of Korea's Intended Nationally Determined Contribution", United Nations Framework Convention on Climate Change, accessed July 12, 2018, http://www4.unfccc.int/ndcregistry/PublishedDocuments/Republic%20of%20Korea%20First/INDC%20Submission%20by%20the%20Republic%20of%20Korea%20on%20June%2030.pdf
17 Choi Ha-yan, "South Korean government releases draft of plans to increase renewable energy use", *Hankyoreh*, 26 December 2017, accessed July 11, 2018, http://english.hani.co.kr/arti/english_edition/e_national/825098.html
18 International Energy Agency Advanced Fuel Cell Technology Collaboration Programme, *National Strategies and Plans for Fuel Cells and Infrastructure*, 2015, accessed July 12, 2018, http://www.ieafuelcell.com/documents/NatStratandPlansforFuelCellsandInfraStruct_v10.pdf
19 *Green Car Congress*, "S Korea to invest $2.3b in hydrogen fuel cell vehicle industrial ecosystem over next 5 years", 25 June 2018, accessed June 12, 2018, http://www.greencarcongress.com/2018/06/20180625-korea.html

Japanese and South Korean Hydrogen Strategies[13]

Japan's *Basic Hydrogen Strategy* was released on 26 December 2017. It highlights goals for 2050 with a detailed action plan through to 2030. One of the primary goals is to reduce the landed cost of hydrogen to the same level as gasoline and LNG, through "integrated policies across ministries ranging from hydrogen production to utilisation".

Japan imports fossil fuels for about 94% of its primary energy supply, making it effectively impossible to meet its goal to cut emissions (from a 2013 baseline) by 26% in 2030 and 80% in 2050. Japan has identified imported hydrogen as a zero-emission fuel that can be used in power generation, mobility, heating and industrial processes.

The strategy identifies the economic opportunity to lead global carbon reduction by creating a new growth industry in hydrogen and fuel cell technologies for domestic and export purposes.

Japan will import hydrogen from low-emission sources at the right price, made from fossil fuels with CCS or from renewable electricity and electrolysis. Experience will be gained by a 2030 import target of 300,000 tonnes of hydrogen (equivalent to 770,000 tonnes of LNG) at a landed cost of ¥30/Nm^3 (A$33/GJ), with a longer-term annual target of up to 10 million tonnes at ¥20/Nm^3 (A$22/GJ).[14]

To facilitate the supply side, by the mid 2020s Japan will demonstrate supply chains for liquefied hydrogen and a liquid organic hydrogen carrier such as methylcyclohexane, both for commercialisation by about 2030.

Japan will use hydrogen for large-scale dispatchable electricity generation. It has numeric targets for mobility, such as 200,000 fuel cell vehicles and 320 hydrogen-refuelling stations by 2025. For its existing industries, it will use hydrogen for energy where electrification is difficult and replace hydrogen made from fossil fuels without CCS. It will invest in developing innovative technologies for high-efficiency electrolysis, highly efficient energy carriers and low-cost fuel cells. (For current hydrogen activity in Japan see Chapter 5.)

The strategy has a very clear commitment for the national government to build community awareness about the safety and the significance of hydrogen, in co-operation with local governments and businesses.

South Korea is a similar market to Japan. It imports about 81% of its energy.[15] Its policies to reduce CO_2 emissions 37% by 2030[16] include increasing the share of electricity generated by renewables from 7% to 20%.[17] The *National Basic Plan for New and Renewable Energies* published in 2014 includes policies and programs likely to increase the uptake of hydrogen technologies.[18] In June 2018 the government announced it would invest, in partnership with private enterprise, more than US$2 billion on hydrogen fuel cell infrastructure, manufacture and technology development.[19] (For other hydrogen activity in South Korea see Chapter 5.)

South Korea's annual demand for hydrogen is forecast to reach up to 170,000 tonnes by 2030, and 500,000 tonnes by 2040.

1.3 Why Australia?

Australia is well-positioned to play a global role in the emerging hydrogen energy market. The development of a hydrogen export industry simultaneously presents diverse flow-on opportunities for domestic decarbonisation of Australia's energy, resources and industrial sectors.

1.3.1 Australia's competitive advantage

Australia is already an energy export superpower. We have expertise and infrastructure that can be leveraged to develop hydrogen energy export supply chains. We are close to key emerging hydrogen import markets in Asia. Our political, social and economic stability, and established regional trading relationships, makes us a trusted trade partner. Low sovereign risk means we are attractive to large infrastructure investors. We have an abundance of renewable energy and low-cost fossil-fuel resources, the latter with adjacent carbon sequestration sites. These factors put Australia in the position to produce and export hydrogen at scale at a competitive cost.

Domestically, as demand for zero-emissions transport increases, heavy vehicles powered by hydrogen fuel cells will have the advantage of long range, rapid refuelling and moderate costs. Emissions from the direct-combustion sector can be substantially reduced by using hydrogen to replace natural gas, taking advantage of appropriately modified existing pipeline networks, storage facilities and appliances. A cheap and plentiful supply of hydrogen means businesses that use it as a chemical feedstock (such as for fertiliser production) can both decarbonise and expand. Hydrogen's capacity as both energy store and flexible load will contribute to a stable and resilient electricity supply.

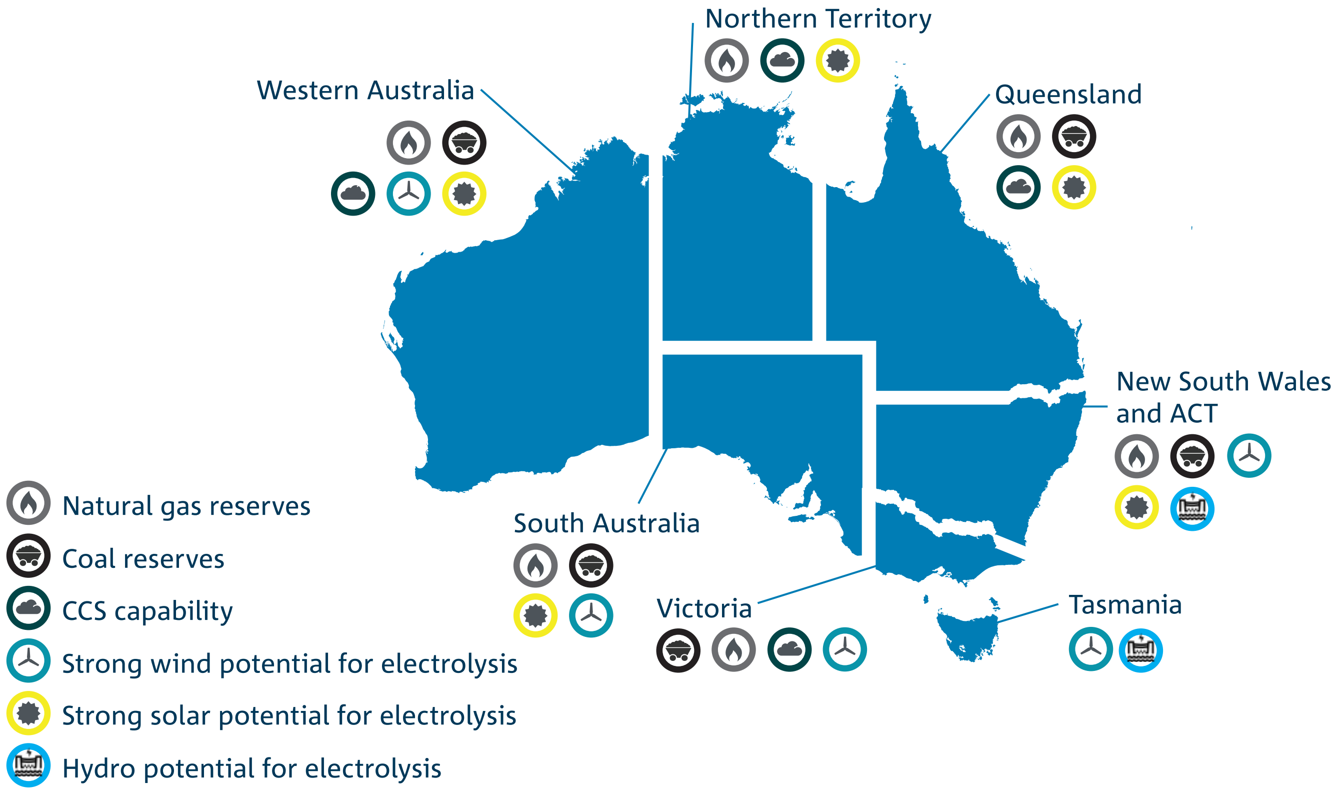
To take advantage of our position requires beating competitors to market. Norway, Saudi Arabia and Brunei are emerging as potential exporters to Japan. Others with plentiful renewable resources or fossil fuel reserves with sequestration sites – the US, for example, or countries in the Middle East and North Africa – could supply a global hydrogen market. The race is on.

1.3.2 Opportunities for states and territories

The main considerations when developing hydrogen energy projects are access to primary energy resources and demand. All states and territories in Australia have world-class renewable energy resources that, when combined with land availability, are attractive areas for investment (see Figure 2). Similarly, some sources of demand, such as for mobility, are expected to be common across the country. Other opportunities vary with location.

Tasmania's renewable hydroelectric and wind resources, for example, are well-suited to electrolyser-based hydrogen production.

South Australia, now a global test bed for various new energy technologies, has hydrogen demonstration projects in the pipeline. Its high proportion of solar and wind electricity makes it an attractive location to invest in hydrogen production and associated industries.



Source: Adapted from Energy Networks Australia 'Gas Vision 2050' (Deloitte Access Economics)

Figure 2: Energy resource options for producing hydrogen across Australia's states and territories.[20]

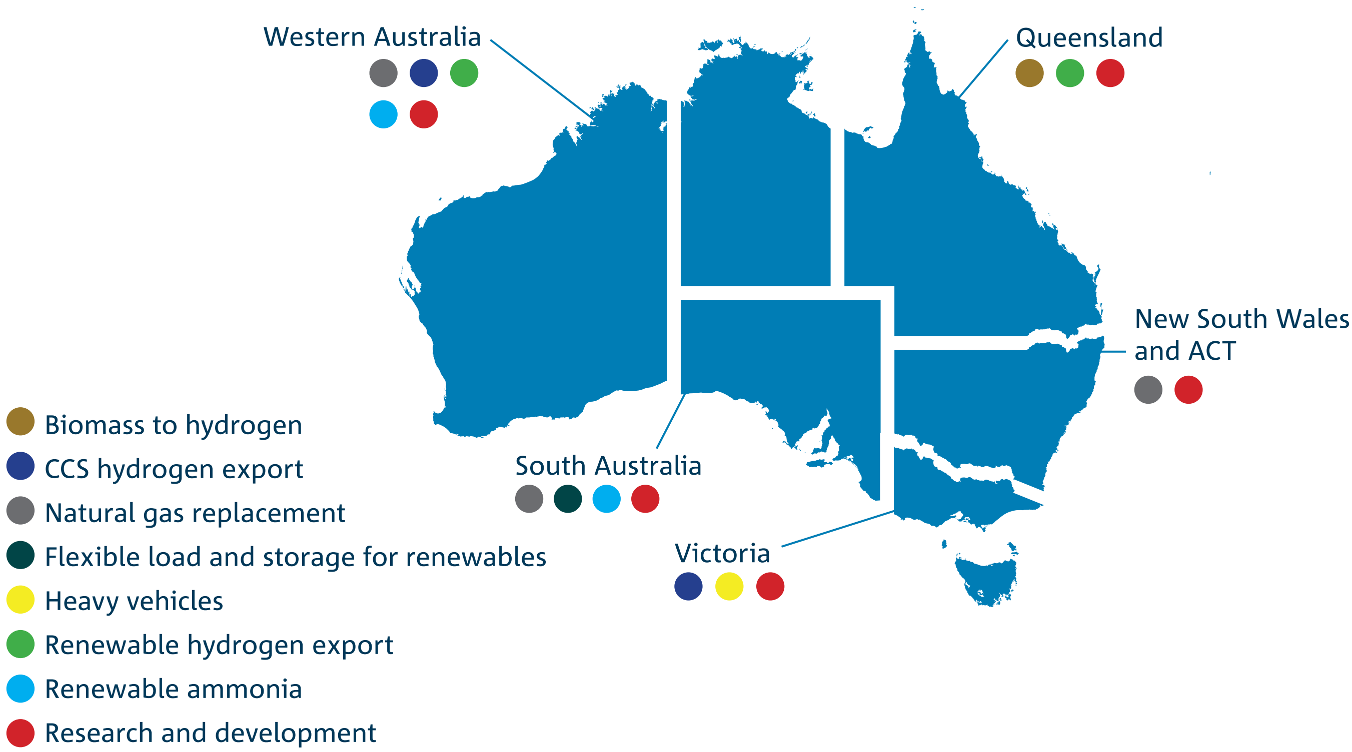


Figure 3: Current hydrogen activity in Australia.

20 Adapted from Deloitte Access Economics, *Decarbonising Australia's gas distribution networks*, 2017.

In Victoria, the vast brown coal reserves and nearby well-characterised carbon storage resources of the Gippsland basin provide a different opportunity. The Hydrogen Energy Supply Chain (HESC) pilot project, trialling processes to produce and export clean hydrogen from the La Trobe Valley to Japan, is under way. Black coal and carbon storage resources in NSW and Queensland present similar opportunities.

The Northern Territory and Western Australia, meanwhile, have extensive natural gas reserves in proximity to depleted gas fields and other sedimentary resources that could be used as CCS reservoirs.[21] They also have abundant solar energy that enables electricity to be generated at some of the highest annual capacity factors in the world. There is good port access, with existing infrastructure for processing and exporting ammonia, fertilisers and LNG that can be partially leveraged to make and move hydrogen. Woodside Energy has already signalled its interest in developing hydrogen production and export facilities in Western Australia's Pilbara region.[22]

1.3.3 Economic and innovation benefits

It is estimated a hydrogen export industry could be worth A$1.7 billion and provide 2,800 jobs by 2030.[23] Given the likely location of hydrogen production, storage and loading for export, these jobs will be in regional areas.

Developing a significant hydrogen production industry focused on export markets will help develop domestic industries that can use hydrogen, and vice versa. There are likely to be spin-off opportunities across the energy, resources, manufacturing, services, transport and education sectors.

As seen in the development of the LNG industry, the need for new skills and infrastructure will spur investment in local communities, creating and increasing government tax and royalty revenue.

Industries using hydrogen as an input should benefit. Ammonia exports, for example, are now worth $US112 million a year, with Australia's share of the global export market being just 1.8%.[24] If demand increases for ammonia produced with low-emission hydrogen, that share could increase substantially.

Hydrogen related expertise can expand Australia's important education export market through the provision of tertiary and vocational training. Expertise in hydrogen project development could be monetised in the same way as oil and gas expertise is exported from Houston, Texas.

21 CSIRO, *Low Emissions Technology Roadmap*, 2017.
22 Peter Williams, "Woodside eyes hydrogen supply for Japan", *The West Australian*, 16 May 2018.
23 ACIL Allen for ARENA, *Opportunities for Australia from Hydrogen Exports*, scheduled for publication August 2018.
24 "Ammonia", MIT Media Lab, accessed July 4, 2018, https://atlas.media.mit.edu/en/profile/hs92/2814/

Technological and business-model innovation offers considerable revenue opportunities. One example is the CSIRO's membrane reactor technology, developed to address a critical need in building ammonia-based hydrogen supply chains.[25] Another example is a new way to economically pipe hydrogen, such as the 'Fluid Highway' technology being developed by Long Pipes Ltd in Western Australia.[26]

There would be direct benefits to the manufacturing sector. Siemens, for instance, has indicated it will consider making its electrolyser systems in Australia if the environment is right. The need for hydrogen piping, storage, welding and testing expertise would also support development of local industries.

Adding hydrogen to the national energy mix provides an indirect economy-wide benefit. Diversification reduces reliance on existing energy supply chains, some of which may be vulnerable in an increasingly uncertain international trade environment. Using locally produced hydrogen to power light and heavy vehicles, either directly or as a feedstock to produce liquid fuels, will reduce pressure on the national liquid fuel reserve.

1.3.4 Consumer benefits

Using hydrogen as an energy delivery mechanism to augment or replace natural gas has a variety of benefits for Australian consumers when compared to the option of eliminating natural gas-associated CO_2 emissions through electrification alone.

Preliminary work suggests repurposing natural-gas networks and appliances for hydrogen will be cheaper in some cases than electrification.

Gas networks have high reliability, being underground and with built-in storage. Using hydrogen as a direct fuel in these networks preserves this benefit.

The availability of hydrogen will ensure consumers have an energy choice with the same emotional and qualitative benefits as natural gas appliances. These include a flame for highly controllable cooking, barbecues plumbed into the mains, space heating, fireplaces and unlimited instantaneous hot water.

In transport, hydrogen presents consumers a greater range of choices for zero emissions mobility. They will be able to choose between hydrogen fuel cell electric vehicles and battery electric vehicles to suit their lifestyle and usage preferences.

25 "Membrane to fill gap in hydrogen energy market", CSIRO, accessed July 5, 2018, https://www.csiro.au/en/News/News-releases/2017/Membrane-for-hydrogen-fuel-cells

26 "The Fluid Highway", Long Pipes Ltd, accessed July 5, 2018, http://www.longpipes.com.au/

2 Hydrogen: a primer

In this chapter we review how hydrogen can be produced, stored and distributed, and the safety considerations that go along with this.

2.1 Hydrogen production

As discussed earlier, hydrogen is an energy carrier. What makes it particularly attractive for this use in Australia is that it can be produced from a wide variety of our abundant fossil fuel and renewable energy sources. Hydrogen energy value chains can therefore readily adapt to changes in the nation's mix of energy sources. We describe two pathways for clean hydrogen production:

1. **CCS hydrogen** – made from fossil fuels like coal or natural gas, with carbon capture and storage (CCS).
2. **Renewable hydrogen** – made from water electrolysis using electricity generated from renewable sources.

Most hydrogen produced now is from fossil fuels without CCS. Of about 55 million tonnes produced, 54 million tonnes is used in industrial processes such as making fertiliser or methanol or refining oil, and is mostly produced at the site at which it is used.[27] Hydrogen production without CCS is not considered further in this report.

2.1.1 Hydrogen production using fossil fuels

In fossil fuel based thermochemical processes used to produce hydrogen, energy from the fossil fuel drives chemical reactions that lead to extraction of hydrogen. In almost all cases CO_2 is a by-product. Some form of CCS is essential if hydrogen from fossil fuels is to deliver decarbonisation benefits. The main processes currently employed are:

Steam methane reforming (SMR) involves catalytically reacting natural gas with steam to produce hydrogen and carbon monoxide (a mixture known as syngas). A subsequent reaction involving more steam produces further hydrogen while also converting carbon monoxide (CO) to CO_2.

Gasification is used for solid feedstocks such as coal and waste biomass. Chemically it is a more complex process than SMR and produces a higher ratio of CO_2 to hydrogen.

Partial Oxidation (POX) and Autothermal Reforming (ATR) use partial combustion processes to generate the heat required to drive the thermochemical reactions of feedstocks such as natural gas, liquefied petroleum gas (LPG), naphtha and heavy oils. Both have higher CO_2 emissions than SMR.[28]

27 Hydrogen Council, *Hydrogen scaling up: A sustainable pathway for the global energy transition*, 2017, accessed July 18, http://hydrogencouncil.com/wp-content/uploads/2017/11/Hydrogen-Scaling-up_Hydrogen-Council_2017.compressed.pdf
28 Steven Rice and David Mann, *Autothermal Reforming of Natural Gas to Synthesis Gas*, Sandia National Laboratories, 2007.

2.1.2 Hydrogen production using renewable energy

Hydrogen production using renewable electricity is growing rapidly. Most commonly, electricity from renewable sources such as wind or solar power is used to drive the electrochemical dissociation (electrolysis) of water to form hydrogen and oxygen. This reaction is also known as water splitting.

The reaction occurs in a device known as an electrolyser, which consists of a positive electrode (anode) and negative electrode (cathode) separated by an electrolyte or a membrane. When an electrical potential is applied between the electrodes, hydrogen is formed at the cathode and oxygen at the anode, with the hydrogen collected for use. The oxygen may also be collected if there is market demand, but for large-scale hydrogen production the quantity produced will greatly exceed demand and so will be released into the atmosphere. Two types of electrolyser system are used commercially.

Alkaline electrolysers are the technologically most mature, and the most widely used. They use an alkaline water solution (typically containing potassium hydroxide) as the electrolyte.

In proton exchange membrane or **PEM electrolysers**, a polymer membrane replaces the alkaline solution. The membrane acts as a more complete barrier to gas transfer between the membranes, resulting in higher efficiency hydrogen production. PEM electrolysers respond more rapidly to variations in electricity supply than alkaline electrolysers. On the other hand, they are also more expensive to make and operate.

Both types of electrolyser require compressors, heat exchangers, water purifiers and pumps to support continuous operation.[29]

Depending on the electrolyser configuration, hydrogen can be produced at atmospheric or elevated pressures. The latter is useful for offsetting costs in subsequent compression steps to store and distribute the hydrogen.

Hydrogen production via electrolysis requires high-purity water. The majority of commercial electrolysers have an integrated deioniser to purify the water. Every 1 kg of hydrogen produced requires 9 kg of water. To get a sense of the amount of water required for large-scale hydrogen production, consider the challenge of producing enough hydrogen to match the energy content of Australia's LNG production. Australia's LNG exports in the 2019 fiscal year are projected to be 74 million tonnes. The energy content is equivalent to about 34 million tonnes of hydrogen, which would require 279 gigalitres of water to be electrolysed. This is a large volume of water but is less than 2.5% of Australia's current annual water consumption, and about half of the water used in Australian mining. It would underpin an export industry of enormous scale.

A third type of technology known as solid oxide electrolysis is under development but not yet commercialised. Solid oxide electrolysis cells have high efficiencies but operate at much higher temperatures than alkaline or PEM electrolysis, so require an external heat source. They are not considered further in this report.

29 CSIRO, *National Hydrogen Roadmap*, 2018.

R&D is also under way to develop other processes for direct water splitting – requiring no electricity as an intermediate energy source. In direct photolysis, sunlight is used to directly decompose water in the presence of a photocatalyst. In thermolysis, direct decomposition of water is achieved using high temperatures (>2,000°C). Pathways for this based on renewable concentrated solar thermal energy are being explored. Neither of these processes is commercially mature and the efficiencies are currently low. They are not considered further in this report.

2.1.3 Hydrogen production from biomass

The reforming and gasification processes described in Section 2.1.1 can also be used to produce hydrogen or biofuels from residual biomass from forestry and agriculture or from waste from other human activities, such as municipal solid waste. Hydrogen produced in this way can be considered low emissions since the CO_2 released from the biomass came from the atmosphere in the first place. Some emissions may be created in collecting the biomass, however. Hydrogen production using biomass can result in net negative emissions if CCS is used.

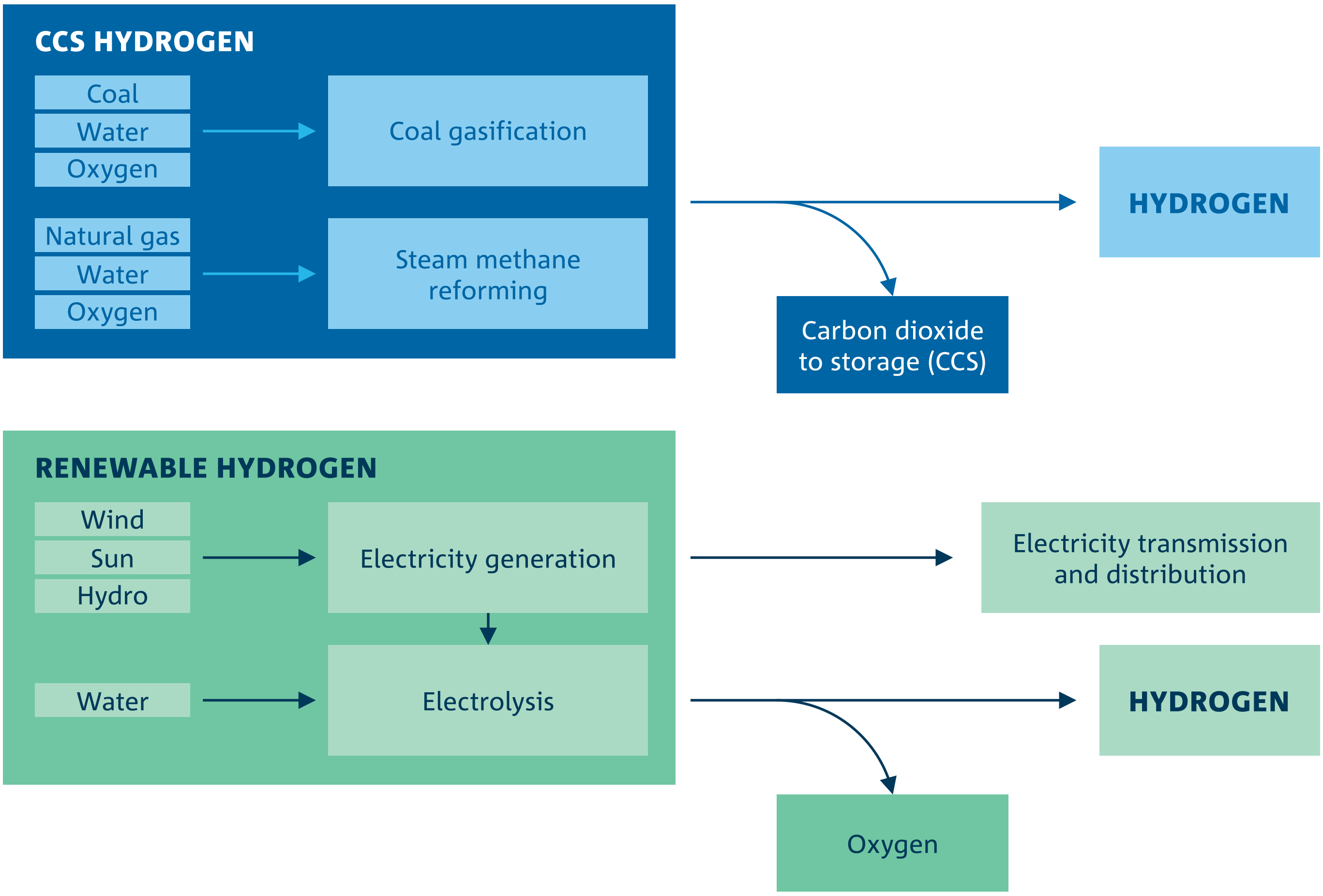


Figure 4: Hydrogen production pathways considered in this report.

Because these biomass production processes would be challenging to do at scale, due to feedstock availability and variability as well as transport costs, they are not considered further in this report.

2.1.4 Hydrogen production costs, efficiencies and emissions

Table 1 below compares current energy efficiencies, costs, and CO_2 emissions of the most widely used production processes. It shows that the fossil-fuel-based processes produce the cheapest hydrogen, and that low emissions can be achieved if CCS is available. While renewable electricity electrolysis technologies currently produce hydrogen at a higher cost, they do so with inherently low emissions. Electrolysis technology is relatively immature, and ongoing volume driven innovation is expected to bring process costs down in the near to mid-term, becoming competitive with thermochemical production processes by 2025.[30] The US Department of Energy has a 2020 cost target for hydrogen by electrolysis of US$2.30/kg (about A$3.10/kg), in line with the estimates by the CSIRO for 2025.[31]

Some process emissions are produced from fossil-fuel-based thermochemical processes even with CCS. Full life-cycle analyses suggest these could compete with electrolysis for emissions reduction but this is not considered here.[32] CCS costs are highly location dependent and the technology has not yet achieved widespread commercialisation. The process emissions figures in Table 1 assume 95% capture efficiency for gasification with CCS, and 90% for SMR with CCS. Note, these process emission figures are not the same as the emissions saved by retiring fossil fuel use in the importing country.

TABLE 1: COSTS, EFFICIENCIES AND CO_2 EMISSIONS FROM DIFFERENT HYDROGEN PRODUCTION PATHWAYS.

PRODUCTION PROCESS	PRIMARY ENERGY SOURCE	HYDROGEN PRODUCTION ENERGY EFFICIENCY (%, LHV)[33]	HYDROGEN PRODUCTION COST A$/KG[34]		HYDROGEN PRODUCTION COST A$/GJ (LHV)[35]		NET PROCESS CO_2 EMISSIONS IN KG CO_2/GJ OF HYDROGEN[36,37]
			2018 ESTIMATE	2025 BEST CASE MODEL	2018 ESTIMATE	2025 BEST CASE MODEL	
Steam methane reforming with CCS	Natural gas	64	2.30-2.80	1.90-2.30	19.20-23.30	15.80-19.20	6.3
Coal gasification with CCS	Coal	55	2.60-3.10	2.00-2.50	21.70-25.80	16.70-20.80	5.9
Alkaline electrolysis	Renewable electricity	58	4.80-5.80	2.50-3.10	40.00-48.30	20.80-25.80	~ 0
PEM electrolysis	Renewable electricity	62	6.10-7.40	2.30-2.80	50.80-61.70	19.20-23.30	~ 0

30 CSIRO, *National Hydrogen Roadmap*, 2018.
31 Mary-Rose de Valladares, *Global Trends and Outlook for Hydrogen*, IEA Hydrogen, 2017.
32 Jamie Speirs et al, *A greener gas grid: What are the options?,* Sustainable Gas Institute, Imperial College London, 2017.
33 LHV stands for Lower Heating Value, which is a more conservative energy rating than the Higher Heating Value (HHV): CSIRO, *National Hydrogen Roadmap*, 2018.
34 CSIRO, *National Hydrogen Roadmap*, 2018.
35 CSIRO, *National Hydrogen Roadmap*, 2018.
36 CSIRO, *National Hydrogen Roadmap*, 2018.
37 CO2CRC, *Australian Power Generation Technology Report*, 2015, accessed July 20, 2018, http://www.co2crc.com.au/wp-content/uploads/2016/04/LCOE_Report_final_web.pdf

2.2 Hydrogen storage and distribution

2.2.1 Pressurised and liquefied hydrogen

Hydrogen is a very light gas. To store and transport it economically over long distances it must be compressed or liquefied; alternatively, it can be chemically converted to a hydrogen-containing liquid or incorporated into a solid substrate, as described in the next section.

Hydrogen liquefaction involves compression and cooling via processes similar to those used in the LNG industry, albeit these are significantly more energy intensive given the lower temperature (–253°C) required. The process consumes 20-30% of the starting energy content of the hydrogen and is capital-intensive. If the liquefaction process uses renewable electricity as its energy source instead of a portion of the hydrogen itself, cost improvements can be expected. Research to improve liquefaction technology, as well as improved economies of scale, could also help lower the cost.

Once hydrogen is liquefied, it can be stored in large insulated cryogenic tanks such as those shown in Figure 5-top. A small amount of stored liquefied hydrogen is lost through evaporation, or ‘boil off’, each day.[38,39]

Figure 5: Hydrogen storage and distribution options; liquefied hydrogen tanks (top), tube trailers (middle) and salt caverns (bottom)[39]

38 Hwalong You et al, “Effect of ortho-para conversion on economics of liquefied hydrogen tanker with pressure cargo tanks”, *Ships and Offshore Structures*, vol. 13, issue sup1, 2018, accessed July 13, 2018, DOI: 10.1080/17445302.2018.1426526

39 *The Truth about Cars*, December 11, 2014, accessed July 13, 2018, https://www.thetruthaboutcars.com/2014/12/sandia-labs-underground-geologic-formations-hold-future-hydrogen-storage/
Images: Heather Paul, flickr CC; BOC hydrogen truck, www.tiapm.it/; https://commons.wikimedia.org/wiki/File:Slanic_Salt_Mine_-_panoramio_(1).jpg

Pressurised hydrogen storage is usually at up to 70 megapascals (MPa)[40] for use in fuel cell electric vehicles such as the Toyota Mirai and Hyundai Nexo. This is about 700 times normal atmospheric pressure.

A variety of pressure vessels can be used for storage and distribution. A compressed hydrogen 'tube trailer' is an example of a storage and transport system, as shown in Figure 5-middle.

One attractive storage and distribution approach which uses existing infrastructure is to inject pressurised hydrogen into natural gas pipelines. This is discussed in more detail in Section 3.2.1.

Hydrogen can be stored in large quantities underground at lower pressures – about 20 MPa – for longer term use.[41] Underground natural gas storage is commonplace around the world, including Australia. Certain types of geological storage used for natural gas are already suitable for storing hydrogen or can be readily repurposed. One example is salt caverns, washed voids in deep geological strata of salt (see Figure 5-bottom) that can be used to store many sorts of gases. The salt is an excellent seal and resilient to fractures. Salt caverns are secure and economical stores given the high tightness of the salt rock mass, relatively low construction costs and the small footprint above ground.

2.2.2 Chemical carriers

Where liquefied or high-pressure hydrogen storage is not possible, two other alternatives can be considered. The first is to chemically convert the hydrogen into a hydrogen-containing liquid. The second is to incorporate the hydrogen into a solid carrier material.

The most prospective forms of liquid carriers are ammonia and liquid organic hydrogen carriers such as methylcyclohexane (MCH). These have high hydrogen storage densities and can be produced at scale using established industrial processes.

Ammonia (NH_3) in particular has a number of favourable attributes as a hydrogen carrier.

- It is a carbon-free fuel that can be directly burned to release energy or decomposed to liberate hydrogen and nitrogen.
- It is a key component of existing industrial products such as fertilisers and explosives.
- It can be transported as a liquid at ambient temperature and mild pressure. It is already shipped at large scale with well-established infrastructure and handling practices.
- The amount of hydrogen that can be transported per ship is likely to be significantly higher with ammonia than with liquefied hydrogen, given ammonia's greater hydrogen density and simpler cooling and physical storage requirements.
- Australia already produces and exports significant quantities.[42]

40 One bar of pressure is equal to 100 kilopascals or 0.1 megapascals and approximately equal to standard atmospheric pressure.

41 "Praxair Signs Long-Term Agreement with Celanese to Supply Carbon Monoxide, Oxygen and Nitrogen in the U.S. Gulf Coast", Praxair, 21 February 2017, accessed July 13, 2018, http://www.praxair.com/-/media/documents/news-releases/2017/praxairsignslongtermagreementwithcelanesetosupplycarbonmonoxideoxygenandnitrogenintheusgulfcoast.pdf

42 "Ammonia", MIT Media Lab, accessed July 1, 2018, https://atlas.media.mit.edu/en/profile/hs92/2814/

Liquid organic hydrogen carriers are substances to which hydrogen atoms can be added and subsequently removed at the destination using heat or catalysts. MCH, for example, is formed by adding hydrogen to toluene ($C_6H_5CH_3$). This enables hydrogen to be stored and transported as a liquid at ambient temperature and pressure.[43] Once the hydrogen is recovered, the liquid toluene can be shipped back to the origin and reused.

The significant energy required for conversion to hydrogen carriers is a challenge. This may be in the form of compression or heat needed to drive chemical reactions. However, the same is true for producing liquefied hydrogen, with energy and capital-intensive infrastructure needed for cryogenic cooling and storage.

Solid hydrogen carrier materials, such as hydrides based on the light-weight elements boron, nitrogen and carbon[44] or highly porous physical hydrogen sorbents, are the subject of much R&D activity but remain a work in progress. The major challenges are related to the slow kinetics of hydrogen uptake and release, and inadequate storage capacity. They are not considered further in this report.

2.2.3 Gas pipelines and networks

Australia's existing natural-gas pipeline infrastructure stores and transports an amount of energy equivalent to 5.4 billion Tesla Powerwall 2 batteries (73 terawatt-hours).[45] Following incremental enhancements, this infrastructure can be used to store and transport hydrogen, either mixed with natural gas or in some cases completely replacing it. This opportunity is discussed in more detail in Section 3.2.1.

2.2.4 Transport in liquid form

Hydrogen is most commonly transported as a liquid when high volumes are needed in the absence of pipelines. Liquefied hydrogen transport is relatively common in the US and Europe but does not yet occur in Australia. Trucks transporting liquefied hydrogen are referred to as liquid tankers.

For long-distance transport by road, liquefied hydrogen is more economical than gaseous hydrogen because a liquid tanker holds a much larger mass of hydrogen than a gaseous tube trailer of equivalent size. Liquefied hydrogen is transported in super-insulated cryogenic tanks to distribution sites where it is vaporised into a high-pressure gas for use by consumers.

There are some challenges in transporting cryogenically cooled or pressurised hydrogen, such as the 'boil-off' during delivery. These can be avoided by chemically converting the hydrogen into a liquid carrier (as discussed in Section 2.2.2) that requires less complex storage engineering. Upon delivery, the liquid carrier can be directly consumed by combustion or chemically reacted to release hydrogen.

43 Patrick Preuster et al, "Liquid Organic Hydrogen Carriers (LOHCs): Toward a Hydrogen-free Hydrogen Economy", *Accounts of Chemical Research*, vol. 50, issue 1, 2017.
44 Teng He et al, "Hydrogen Carriers", *Nature Reviews Materials*, vol. 1, issue 12, 2016.
45 Energy Networks Australia, *Gas Vision 2050*, 2017; calculation updated July 2018.

For long-distance transport by ship, there are competing cost and efficiency benefits for liquefying hydrogen versus converting it to a liquid carrier. As yet there is insufficient practical engineering experience to know which will be the most effective at large scale. New ships will be required to carry liquefied hydrogen, such as the one being built as part of the HESC pilot project in Victoria.

Current cost estimates for both liquefaction and liquid carrier conversion and reconversion to hydrogen are very high – the cost of liquefaction, for instance, is estimated at $1.30/kg.[46] However, research and development, innovation and practical experience from the likes of the HESC project should bring these costs down.

2.3 Safety considerations for storage and distribution

Given their combustible nature, all conventional fuels have some degree of risk associated with their use. Although hydrogen is a different fuel to natural gas and has different combustion characteristics, a preliminary analysis by the Energy Pipelines Cooperative Research Centre indicates its overall risk is similar.[47]

Compared with natural gas:

- Hydrogen is lighter. It rises six times faster than natural gas. If it leaks from a pipe or appliance, it will disperse much more quickly and is not as likely to collect in confined spaces, reducing the risk of a gas explosion.
- Hydrogen ignites at a wider range of concentrations in air. Its flammability range is between 4% and 75% in air, while that of natural gas is between 5% and 15%. However, because hydrogen disperses quicker, it is more difficult for it to remain concentrated enough to be flammable. Adequate ventilation and leak detection protocols can mitigate any potential greater risk.
- Hydrogen flames are more difficult to see. A common concern with burning hydrogen is its reduced visibility compared with the bright blue colour of natural gas. This can be addressed by adding a suitable compound to the hydrogen mix so the flame burns a particular colour, or by using special flame detectors.
- Hydrogen has no odour therefore cannot be detected by the sense of smell. The solution is to add odorants at very low concentration levels.[48]
- Hydrogen is non-toxic.
- Hydrogen reacts differently with metals. It can cause certain metals to become brittle and crack. High-strength steels, titanium alloys and aluminium alloys are the most vulnerable.[49] This can be addressed through guidelines on appropriate materials and training on handling hydrogen.

Using any fuel safely relies on preventing the simultaneous unwanted occurrence of three factors: an ignition source (spark or heat), an oxidant (air), and fuel. With proper information, guidelines, education and engineering expertise, fuel systems can be designed to avoid the simultaneous occurrence of these three factors.[50]

46 Analysis provided by CSIRO based on data from the *National Hydrogen Roadmap*, 2018.
47 Energy Pipelines Cooperative Research Centre, *Research Report: Identifying the commercial, technical and regulatory issues for injecting renewable gas in Australian distribution gas networks*, July 2017.
48 Deloitte Access Economics, *Decarbonising Australia's Gas Distribution Networks*, 2017.
49 "Hydrogen embrittlement", NACE International, accessed July 13, 2018, https://www.nace.org/Corrosion-Central/Corrosion-101/Hydrogen-Embrittlement/
50 "Safe Use of Hydrogen", US Department of Energy's Office of Energy Efficiency and Renewable Energy, accessed July 1, 2018, https://www.energy.gov/eere/fuelcells/safe-use-hydrogen

2.4 Some properties of hydrogen

	ENERGY CONTENT		VOLUME	EQUIVALENT ENERGY TO	DRIVING DISTANCE EQUIVALENT TO**
1 kg of hydrogen	120 MJ*	33.33 kWh	14 litres of liquefied hydrogen at –253°C#	4 litres of petrol[51]	8 litres of petrol
1 metric tonne of hydrogen	120 GJ*	33.33 MWh	14 m^3 of liquefied hydrogen at –253°C	2.4 tonnes of liquefied natural gas (LNG)	

*** The lower heating value (LHV) of hydrogen is used throughout this document unless otherwise stated.**

 # -253°C is 20°K. For comparison, natural gas liquifies at -162°C or 111°K.

**** Because of the greater energy efficiency, a fuel cell vehicle drives two or more times further than an equivalent petrol car starting with the same fuel energy in a full tank. This efficiency ratio is often referred to as the energy economy ratio (EER).[52,53]**

Price examples

- $20/GJ hydrogen = $2.40 per kilogram of hydrogen.
  - Morgan Stanley Research estimates the 2030 wholesale price of renewable hydrogen will be €1.80 per kg (A$2.85 per kg).[54]
- Retail fuel cost per kilometre driven
  - A mid-size Toyota Mirai travels more than 100 km per kg of hydrogen[55]
  - A petrol car using 8 litres per 100 km at A$1.40 per litre costs 11.2 cents per km
  - A hydrogen car using 1 kg hydrogen per 100 km at A$11 per kg costs 11 cents per km
  - Thus A$11 per kg hydrogen at retail refuelling stations is the target for petrol price equivalence. Current refuelling stations in California sell hydrogen at an average of A$19 per kg, with prices expected to fall substantially as the number of refuelling stations and their utilisation increases.[56]

51 Fuel conversion factors, accessed July 24, 2018, https://epact.energy.gov/fuel-conversion-factors
52 "Full Fuel Cycle Analysis Assessment", California Energy Commission, accessed July 23, 2018, http://www.energy.ca.gov/ab1007/documents/2006-10-16_joint_meeting/presentations/2006_10-16_FFCA_AB1007.PDF
53 Data on well-to-wheels energy use, greenhouse gas emissions and criteria pollutant emissions in "Full Fuel Cycle Analysis Assessment", California Energy Commission, accessed July 23, 2018.
54 Morgan Stanley Research, *Global Hydrogen,* 2018
55 "Mirai fuel cell vehicle", Toyota, accessed July 24, 2018, https://s3-eu-west-1.amazonaws.com/liveassets.toyotaretail.co.uk/flipbook/IE_PDF/mirai.pdf
56 "Cost to refill", California Fuel Cell Partnership, accessed July 24, 2018, https://cafcp.org/content/cost-refill

3 The hydrogen opportunity

Hydrogen's versatility means it can play a key role across all energy sub-sectors. It can be used as an exportable zero-emissions fuel. It can be burned to provide heat for buildings, water and industrial processes. It can power transport through fuel cells, being particularly suitable for long-haul heavy transport. It can help make the entire energy system more resilient by providing a flexible load, frequency control services and dispatchable electricity generation. It can help diversify the nation's fuel mix. These uses are explored further in this chapter.

3.1 A new export industry

Australia is the world's biggest exporter of coal and second-biggest exporter of natural gas. As such these industries make a significant contribution to the nation's prosperity. Hydrogen provides a means to develop a new export industry that can supplement them. It enables Australia to secure its position in the emerging market for low and zero emissions energy using both its fossil-fuel reserves and its enormous capability to produce renewable electricity.

There are two ways to export renewable energy in large scale:

- Via electricity through undersea high voltage direct current (HVDC) cables.
- Via transportable commodities such as biofuels, synthetic fuels and hydrogen.

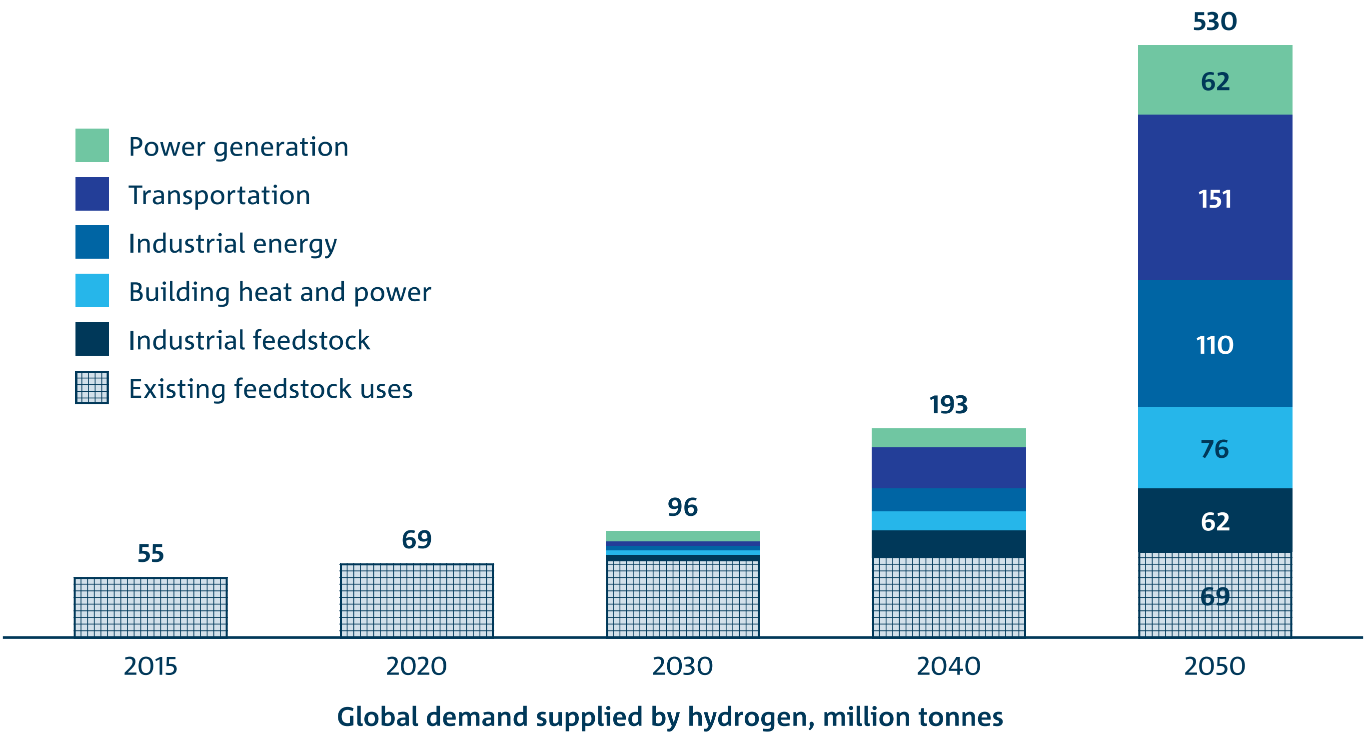


Figure 6: The Hydrogen Council's forecast growth in demand for hydrogen to 2050.[57]

57 Adapted from Hydrogen Council, *Hydrogen scaling up: A sustainable pathway for the global energy transition*, 2017. Assumes 55Mt demand in 2015 and growth rates as per report.

As outlined in Chapter 2, hydrogen can be stored and transported in liquefied form or in the form of other liquids such as ammonia or methylcyclohexane (MCH). These pathways are discussed further below. Unlike electricity transferred through HVDC cables, hydrogen can be stored and exported to any destination with appropriate import facilities, and is less dependent on a single piece of infrastructure or supplier. Compared with biofuels and synthetic fuels, hydrogen supply chains produce fewer life-cycle CO_2 emissions and emit no pollution at the point of use.

As well as being exported as an energy carrier, hydrogen can be embodied into low-emissions products to compete in the world market. For example, hydrogen can be used to chemically reduce iron ore into pig iron ingots for export. Another possibility is to use hydrogen to produce low-emissions ammonia for fertiliser and increase Australia's share of the global ammonia export market.[58,59]

Potential markets for hydrogen are countries that:

- Are or are likely to become net importers of energy.
- Have limited potential to economically expand their domestic renewable energy production.
- Have ambitious carbon abatement targets.

Two such countries are Japan and South Korea, both of which have national strategies for hydrogen and are key markets for Australian energy exports.[60]

Key end uses for hydrogen in these markets are:

- Powering fuel cell vehicles.
- Large-scale electricity generation.
- Decarbonising natural gas networks by replacing methane with hydrogen.
- Producing electricity and heat in residential fuel cells.

3.1.1 Potential scale of hydrogen exports

Global demand for hydrogen is now about 55 million tonnes a year (with the same energy content as 132 million tonnes of LNG). Almost all of it is used to refine oil or produce ammonia and other chemicals.

It is estimated about 1 million tonnes is used for energy. Relatively conservative assumptions suggest this part of the market could grow to more than 8 million tonnes by 2030 and about 35 million tonnes by 2040.[61]

Australia could feasibly be exporting about 137,000 tonnes of hydrogen a year by 2025, about 500,000 tonnes by 2030, and about 1.4 million tonnes by 2040.[62] Japan, South Korea and China are the likely key markets. The United States and Europe, though potentially huge users, are less promising markets because they have the resources to develop sufficient domestic supply. Other markets such as Taiwan, India and Thailand are possible customers but currently have weaker policies to drive demand.

58 Venkat Pattabathula and Jim Richardson, "Introduction to Ammonia Production", *CEP Magazine*. September 2016, accessed July 12, 2018, https://www.aiche.org/resources/publications/cep/2016/september/introduction-ammonia-production.
59 CSIRO, *National Hydrogen Roadmap*, 2018.
60 Australian Trade Commission, *Trade and Investment Note: Australia's export performance in FY2017*, December 2017, accessed July 12, 2018, https://www.austrade.gov.au/ArticleDocuments/5720/Australias_export_performance_FY2017.pdf.aspx?Embed=Y
61 Medium hydrogen uptake scenario in: ACIL Allen for ARENA, *Opportunities for Australia from Hydrogen Exports*, 2018.
62 ACIL Allen for ARENA, *Opportunities for Australia from Hydrogen Exports.*

To supply the potential 2030 export market of 500,000 tonnes would require more than 30,000 GWh of electricity.[63] To put that in context, Australia's 2020 Large-scale Renewable Energy Target (LRET) is 33,000 GWh, while the total electrical energy generated in the National Electricity Market (NEM) in 2017 was 197,000 GWh.[64]

3.1.2 Export supply chain pathways

As discussed in Chapter 2, due to its low density, hydrogen must be liquefied or attached to a chemical carrier such as ammonia or methylcyclohexane (MCH) for long-distance transport.

The liquefied hydrogen pathway: Substantial energy is used in liquefaction. Conversion back to gaseous hydrogen at the destination is simple and does not require much energy.

The ammonia pathway: Energy is used to convert hydrogen and nitrogen into ammonia. Conversion back to gaseous hydrogen at the destination requires energy and chemical processing. The waste product is harmless nitrogen gas, which is released to the atmosphere.

The MCH pathway: Energy is used to convert toluene and hydrogen into MCH. Conversion back to hydrogen gas at the destination requires energy and chemical processing. The toluene is captured and shipped back to the producer to make more MCH.

Exporting hydrogen via solid carriers is much less technologically mature than the other methods and unlikely to be commercial in the near future.

Preliminary costs have been estimated for the liquefied hydrogen pathway (Figure 7).

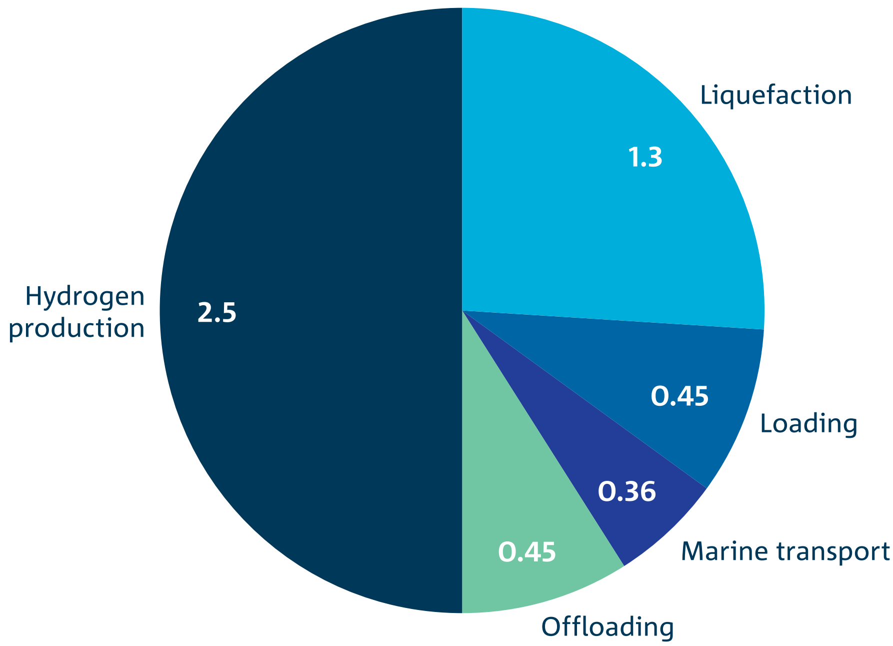


Figure 7: Delivered cost in A$/kg of liquefied hydrogen to Japan (2025 figures from the CSIRO Roadmap). [65]

63 Assuming 50% cumulative loss from electrolysis, compression, pipeline transport and liquefaction.
64 "The Australian Energy Market", Australian Energy Market Operator, accessed July 12, 2018, https://www.aemo.com.au/-/media/Files/Electricity/NEM/National-Electricity-Market-Fact-Sheet.pdf
65 Analysis provided by CSIRO, based on data from the *National Hydrogen Roadmap*, 2018.

The ammonia and MCH pathways are expected to have broadly similar delivered costs to the liquefied hydrogen pathway.[66] However, the required technology is yet to be demonstrated at scale, and the most efficient and cost-effective processes will be determined over coming years.

For liquefaction, the greatest opportunity to reduce costs is likely to come from the decreasing price of renewable energy, which can be used to power the process.

A cost-effective ammonia pathway will depend on technologies to purify the hydrogen produced when decomposing the ammonia at the destination. Alternatively, technological development may make it feasible to use the ammonia directly, such as for powering turbines to generate electricity, as Japan plans to do by 2030.[67]

A number of hydrogen export demonstration projects to ship hydrogen to Japan are under development. Projects announced or being explored include:

- CCS hydrogen derived from brown coal shipped from Victoria as liquefied hydrogen.[68]
- Hydrogen produced by steam reforming shipped from Brunei as MCH.[69]
- Hydrogen produced from hydro and wind electricity shipped from Norway as liquefied hydrogen.[70]
- Hydrogen produced from oil reforming shipped from Saudi Arabia as ammonia.[71]

3.2 Opportunities for the domestic economy

3.2.1 Heating

Direct combustion is responsible for 18% of Australia's carbon emissions.[72] About half of these emissions result from the combustion of natural gas for heat.[73] Heating services are currently supplied in Australia from direct combustion of fossil fuels and electricity mostly generated from fossil fuels, solar thermal and biomass.

66 Yuji Mizuno et al, "Economic analysis of international hydrogen energy carrier chain", *Journal of Japan Society of Energy & Resources,* vol. 38, issue 3, May 2017.

67 Ministerial Council on Renewable Energy, Hydrogen and Related Issues, *Basic Hydrogen Strategy*, 2017, accessed July 12, 2018, http://www.meti.go.jp/english/press/2017/pdf/1226_003b.pdf

68 Kellie Lazzaro, "World-first coal to hydrogen plant trial launched in Victoria", ABC News, 12 April 2018, accessed July 12, 1018, http://www.abc.net.au/news/2018-04-12/coal-to-hydrogen-trial-for-latrobe-valley/9643570

69 "The world's first global hydrogen supply chain demonstration project", AHEAD, accessed July 12, 2018, https://www.chiyodacorp.com/meida/170727_e.pdf

70 Lefteris Karagiannopoulos et al, "Norway races Australia to fulfill Japan's hydrogen society dream", Reuters, 28 April, 2017, https://www.reuters.com/article/us-japan-hydrogen-race-idUSKBN17U1QA

71 Stephen Crolius, "Japan, Saudi Arabia explore trade in hydrogen, ammonia", *Ammonia Energy*, 15 February, 2018, http://www.ammoniaenergy.org/japan-saudi-arabia-explore-trade-in-hydrogen-ammonia/

72 Department of the Environment and Energy, *Australia's emissions projections 2016*, December 2016; direct combustion includes emissions from burning coal and gas for industrial and building heat, steam and pressure as well as emissions from combustion of fuel for mobile equipment in mining, manufacturing, construction, agriculture, forestry and fishing.

73 Share of emissions for heating using natural gas estimated from Australian Bureau of Statistics, *Year Book Australia, 2012*, and Department of the Environment and Energy, *National Greenhouse Accounts Factors*, August 2016.

Decarbonising Australia's heating demand requires alternatives to fossil fuels. Electrification using renewable electricity can play a significant role in this, and there is scope to increase solar thermal and biomass-based heat production.

For many applications, hydrogen is the best option for replacing fossil fuels, particularly natural gas. Since hydrogen is a combustible gas, it can be used in similar ways, using much of the same infrastructure and providing many of the same benefits.

Burning gas to produce heat has long been a part of Australia's energy consumption. From the early 19th century we relied on town gas, a mixture of carbon monoxide and hydrogen made from coal. This was replaced with natural gas in the 1960s, following the discovery of significant reserves.[74] Almost 70% of Australian homes now use mains natural gas or bottled propane gas.[75]

Australia consumed 1,328 petajoules of natural gas in 2015-16, of which 572 petajoules was used for electricity generation.[76] The bulk of the remainder was used for low-temperature heat (<250°C), mostly in the residential and commercial sectors, and for high-temperature applications in industry and mining.[77]

Low-temperature applications include space heating, water heating and cooking. Hydrogen can be used for these applications in similar ways to natural gas. Other low-carbon options include electric heat pumps and solar thermal technologies.

Transitioning to hydrogen for residential and commercial use can be done initially by injecting small concentrations of hydrogen into the existing gas grid. Current household gas appliances are certified to use with a gas blend of up to 13% hydrogen.[78] Above that, modifications will be required for appliances and some of the pipeline infrastructure. For this reason, switching to 100% hydrogen will require a co-ordinated system rollout. This is being explored in Britain (see Section 5.4).

Gas meters would not need to be changed for the initial injection of small concentrations of hydrogen into the gas grid but would need to be changed for the switch to 100% hydrogen.[79]

High-temperature industrial uses of heat include in kilns and furnaces, with the main users in Australia being producers of alumina, cement, iron and steel. For these applications, hydrogen provides the most viable means for decarbonisation, replacing natural gas using existing equipment with minimal retrofit required. Using hydrogen for these high-temperature processes could reduce Australia's industrial need for natural gas by about 154 petajoules.[80]

Using natural gas infrastructure for hydrogen

Much of the existing natural gas pipeline infrastructure can be used for hydrogen with minimal retrofit.

74 Tony Wood et al, *Gas at the crossroads*, Grattan Institute, October 2014, accessed July 12, 2018, https://grattan.edu.au/wp-content/uploads/2014/10/817-gas-at-the-crossroads.pdf
75 Energy Networks Australia, *Gas Vision 2050*, March 2017, accessed July 12, 2018, https://www.energynetworks.com.au/sites/default/files/gasvision2050_march2017_0.pdf
76 Department of the Environment and Energy, *Australian Energy Update 2017*, August 2017.
77 Bureau of Resources and Energy Economics, *Energy in Australia 2012*, February 2012.
78 Energy Networks Australia, Decarbonising Australia's Gas Networks, December 2017, accessed July 12, 2018, http://www.energynetworks.com.au/sites/default/files/2017_-_decarbonising_networks_final.pdf
79 Paul Dodds and Stéphanie Demoullin, "Conversion of the UK gas system to transport hydrogen", *International Journal of Hydrogen Energy*, vol. 38, issue 18, June 2013.
80 Excluding mining, which uses about 175 petajoules of natural gas a year but mainly at lower temperatures.

The extent to which existing natural gas transmission pipelines, which carry gas long distances from gas processing plants to storage close to urban areas, can be used for hydrogen will depend on a number of factors.

These pipelines are predominantly made of steel and operate at pressures >1 MPa. Their ability to transport 100% hydrogen will depend on their susceptibility to the embrittlement caused by hydrogen in some metals. Risk factors include the condition of the pipe and welds, grade of steel, thickness, types of welds and operating pressure.

Hydrogen's properties also means there are differences to natural gas in how it flows through pipes and burns. This may place limits on the amount that can be added to natural gas, with the exact amount depending on the pipeline material and gas pressure. Further, the amount of energy stored in a given length of pipe will be lower when hydrogen is introduced.

Whether it makes sense to use existing natural gas transmission pipelines to transmit 100% hydrogen will also depend on the proximity of hydrogen production to those pipelines. In many cases, it can be expected new pipelines will be needed. Existing pipelines not used to transmit hydrogen may prove useful for hydrogen storage once no longer needed for natural gas.

The gas distribution pipes transporting natural gas from local storage to end users can be more readily repurposed for hydrogen, due to the extensive upgrade work that has already taken place to replace all old cast iron or steel gas pipes with new-generation polyethylene or nylon pipes. This means much of the distribution infrastructure is already compatible with 100% hydrogen.

Electrification and hydrogen

Decarbonisation efforts in the energy sector are currently focused largely on electricity. However, if, over the decades, deep decarbonisation is to be pursued then the heat sector supplied by natural gas will also need to be decarbonised. Australian Gas Infrastructure Group with input from Deloitte has modelled two pathways to decarbonise the whole of Victoria's gas consumption based on 2017 energy consumption data.[81]

The first pathway analyses replacing all natural gas consumption by electricity generated from renewable sources (full electrification). The second pathway analyses upgrading existing natural gas distribution networks for hydrogen produced from renewable generation and electrolysis (hydrogen conversion). Both pathways include the cost to fully decarbonise the existing electricity sector (base case).

The modelling is for comparison purposes only – that is, the relative prices are important. For the base case and the two pathways it is assumed the changeover is effectively instantaneous, and priced on projected 2030 costs from the Australian Electricity Market Operator. In reality, both pathways will take several decades to complete in an orderly fashion, so the actual costs will benefit from normal replacements, further experience-driven cost reductions, digitalisation of the grid operation, demand response and improved efficiency.

81 Australian Gas Infrastructure Group, *Decarbonising Gas Distribution Networks*, scheduled for publication August 2018.

The key points arising from the analysis are:

1. Both pathways require significant investment in renewable energy storage, generation and distribution infrastructure over and above what is required to decarbonise the existing electricity sector, as would be expected.

2. In the full electrification pathway, instantaneous electricity demand increases by 90%. This requires significant investment in renewable generation and electricity storage capacity as well as network upgrades. The significant extra energy storage resources will be particularly important to meet demand during periods where renewable generation output drops for several days due to simultaneous lack of sun and wind. This storage requirement could be met by large-scale pumped hydro storage (both Snowy Hydro 2.0 and potential Tasmanian resources), which is more cost-effective than meeting the full need through battery storage (though extra battery storage will also be needed).

3. The hydrogen conversion pathway is about 40% less than the additional cost of the full electrification pathway due in large part to the flexibility of electrolysis to meet gas demand, with less need for long-term electricity storage though batteries or hydro. However, there will be a need for more long-term hydrogen storage, the costs for which are not well understood in the Australian context. Network upgrade costs are significantly lower compared with the full electrification scenario due to using existing gas network infrastructure.

   The hydrogen conversion pathway also has the benefit, through the widespread deployment of electrolysis, of adding flexible load to the electricity system that can respond to peaks and troughs in both renewable electricity generation and consumer demand. This provides a means to get greater value out of the required 'overbuild' of renewable energy generation by using energy excess to consumer demands.

3.2.2 Hydrogen for mobility

Road transport is responsible for about 15% of carbon emissions, with rail, sea and air transport accounting for 3%.[82] Ultralow emissions vehicles – battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs) – are therefore key to reducing emissions.[83]

Both BEVs and FCEVs use an electric drivetrain. In BEVs, electricity from an external supply charges a battery, which in turn supplies electricity for the motor. In FCEVs, as shown in Figure 8, electricity for the motor is generated by a fuel cell using hydrogen. Both vehicle types produce zero tailpipe emissions, making them ideal for combatting air-quality issues in urban environments. Overall 'well-to-wheel' carbon emissions depend on the source of electricity or hydrogen.

FCEVs and BEVs have complementary roles to play. FCEVs have longer ranges and faster refuelling and are particularly well-suited to long-distance heavy transport where the size and weight of the battery required becomes impractical. BEVs currently have greater model availability, are more than twice as

82 Department of the Environment and Energy, *National Inventory Report 2016, Volume 1*, April 2018, accessed July 19, 2018, http://www.environment.gov.au/system/files/resources/02bcfbd1-38b2-4e7c-88bd-b2b7624051da/files/national-inventory-report-2016-volume-1.pdf

83 Hybrid vehicles also produce fewer emissions than full petrol or diesel vehicles and are expected to contribute to emissions reductions in the short to medium term but cannot achieve the zero emissions required for long-term decarbonisation.

efficient and rely on less expensive refuelling infrastructure. Both technologies face barriers to displacing internal combustion vehicles, including higher upfront costs, lack of trust in a new technology, lack of certainty around policies, incentives and taxes, and limited supporting infrastructure.

Light passenger vehicles and buses

It is expected BEVs will dominate the market for private light passenger vehicles.[85] The uptake of light FCEVs is likely to be greater in specialised markets, such as fleet sales. This is because much less refuelling infrastructure is required as most fleets run within a specified area such as a city (e.g., delivery vans) or on a single site (e.g., forklifts) and can operate with a 'back-to-base' refuelling system.

Greater range and quicker refuelling times translate to higher vehicle availability and productivity compared to BEVs. Fleets often operate with a single model type and can leverage buying power to reduce purchase costs.

Demand for FCEVs may increase as self-driving technology and vehicle sharing develop. An autonomous vehicle fleet can be programmed to return to a single refuelling base, reducing the need for refuelling infrastructure.

There have been a number of hydrogen bus fleet demonstrations – including one in Aberdeen using renewable hydrogen[86] and another in London using hydrogen from SMR[87] – that show FCEVs can meet the performance requirements of public transport. There is strong competition, however, from BEV buses being made in rapidly increasing numbers, mostly in China.[88]

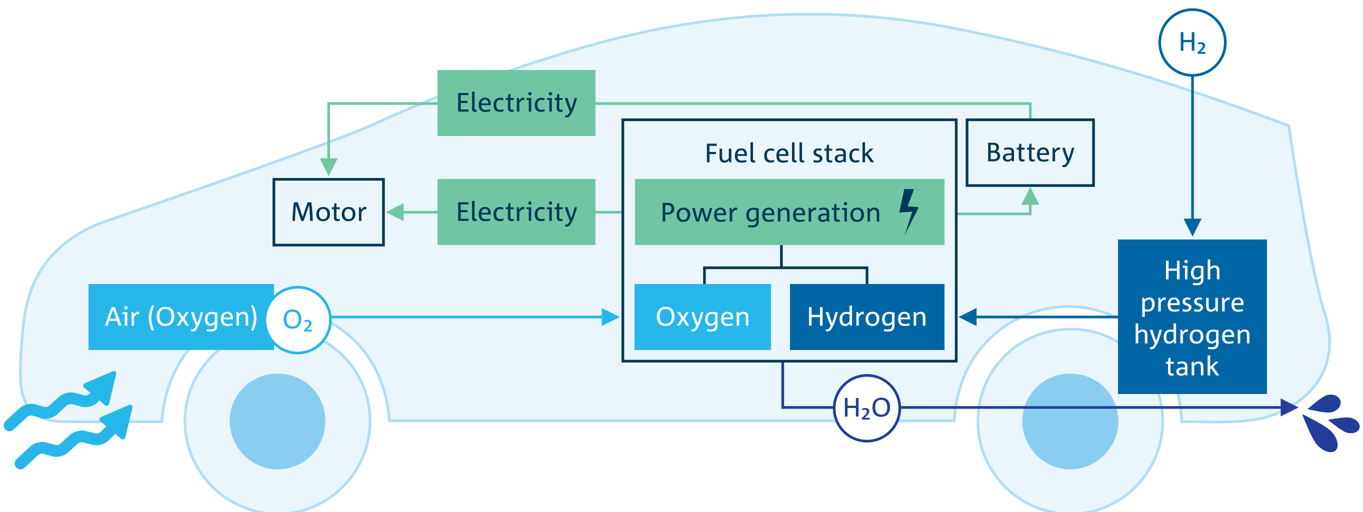


Figure 8: Fuel cell electric vehicles contain a fuel cell stack and a hydrogen tank as well as a small battery.[84]

84 Image courtesy of Toyota.
85 Energia, *Australian Electric Vehicle Market Study*, 2018, accessed July 12, 2018, https://arena.gov.au/assets/2018/06/australian-ev-market-study-report.pdf
86 "Fuel cell zero-emissions buses for Aberdeen, Scotland", Ballard, accessed July 12, 2018, http://ballard.com/docs/default-source/motive-modules-documents/aberdeen-case-study.pdf?sfvrsn=2
87 "Fuel cell zero-emission transit for the city of London", Ballard, accessed July 12, 2018, http://ballard.com/docs/default-source/motive-modules-documents/tfl-case-study-dec-2017.pdf?sfvrsn=2
88 Bloomberg New Energy Finance, *Electric Vehicle Outlook 2018*, 2018.

Heavy vehicles

The greatest opportunity for FCEVs is in the heavy vehicle market, particularly for long-distance trucks. This is largely due to the weight advantages of hydrogen versus batteries. For example, a BEV truck with a gross weight of 20 tonnes and a range of 960 km currently needs a 14 tonne battery, restricting cargo weight and increasing the cost of transportation.[89] For hydrogen vehicles, increasing the range only requires increasing the size of the hydrogen tank, which has less effect on total vehicle weight. Since overall size is typically less of a concern than in light vehicles, heavy FCEVs can store hydrogen in a bigger tank at a lower pressure (30 MPa compared with 70 MPa for light FCEVs), which costs less to compress and requires a lighter storage tank per kilogram of hydrogen.[90]

Plans for hydrogen-powered semi-trailer trucks are already well-developed. The Nikola Motor Company in the US, for example, is looking to build the trucks and refuelling infrastructure, operating on a lease system that includes fuel.[91] The Nikola One semi-trailer truck, due to be commercially available in 2020, will be able to travel up to 1,900 km on a single tank of hydrogen. It is a 'series hybrid' in which the fuel cell charges a battery that drives the electric motor.[92] Brewing company Anheuser-Busch has ordered up to 800 of the trucks.[93]

Figure 9: The Nikola One semi-trailer truck.[94]

Other transport sectors

One of the first commercial applications for FCEVs has been in materials handling, such as forklifts. The advantages are readily apparent in warehouse operations, where air quality is an issue, and where fast refuelling makes FCEVs more productive, and therefore more cost-effective, than BEVs.[95] Hydrogen fuel cells can also power other forms of transport such as trains,[96] ships[97] and even light aircraft,[98] with examples of all of these being demonstrated globally. Australia's rail system could be well-suited to hydrogen. Only 10% of the network is currently electrified. To decarbonise the rest of the network, building hydrogen refuelling infrastructure could be cost-competitive with electrification.[99]

89 Based on current technology. Shashank Sripad and Venkatasubramanian Viswanathan, "Performance Metrics Required of Next-Generation Batteries to Make a Practical Electric Semi Truck", *ACS Energy Lett*ers, vol. 2, issue 7, 2017.
90 Sandy Thomas, "Fuel Cell and Battery Electric Vehicles Compared", National Hydrogen Association Conference and Hydrogen Expo, 2014, accessed July 12, 2018, https://www.energy.gov/sites/prod/files/2014/03/f9/thomas_fcev_vs_battery_evs.pdf
91 "Nikola Two", Nikola Motor Company, accessed July 12, 2018, https://nikolamotor.com/two
92 "Nikola One", Nikola Motor Company, accessed July 12, 2018, https://nikolamotor.com/one
93 Jennifer Smith, "Anheuser-Busch will buy Nikola's hydrogen-powered trucks", The Wall Street Journal, 3 May 2018, accessed July 19, 2018, https://www.wsj.com/articles/anheuser-busch-will-buy-nikolas-hydrogen-powered-trucks-1525352410
94 "Nikola One", Nikola Motor Company.
95 CSIRO, *National Hydrogen Roadmap*, 2018.
96 E4Tech, *The Fuel Cell Industry Review 2017*, 2017.
97 "Cutting through the hydrogen hype", The Motorship, 12 September 2017, accessed July 12, 2018, http://www.motorship.com/news101/fuels-and-oils/cutting-through-the-hydrogen-hype
98 Sophie Morlin-Yron, "The plane that runs on hydrogen and emits only water", CNN, 20 October 2016, accessed July 12, 2018, https://edition.cnn.com/travel/article/hy4-fuel-cell-plane/index.html
99 Bureau of Infrastructure, Transport and Regional Economics, *Trainline 2: Statistical Report*, 2014, accessed July 13, 2018, https://bitre.gov.au/publications/2014/files/trainline_002.pdf

Building FCEV refuelling networks in Japan and South Korea

With the Japanese government having set a target of 40,000 FCEVs on the road by 2020, Japan's automotive industry is already invested in FCEVs. To spread the risk and cost of developing a refuelling network for these vehicles, a consortium of 11 companies including Toyota, Honda and Nissan has been formed, called 'Japan H_2 Mobility'. The group aims to attract further investment in hydrogen infrastructure, taking advantage of current government subsidies that halve the A$5 million cost of building a hydrogen refuelling station. About 100 stations have been built and another 80 are planned in the next four years, with stations being built without subsidies during the second half of the 2020s.

South Korea is also seeking to use public-private partnership to finance hydrogen-refuelling infrastructure.[100] This co-ordinated investment is intended to solve the chicken-and-egg problem of FCEV uptake requiring refuelling stations and refuelling stations requiring an FCEV market to be economic. Careful consideration of locations is required, with hydrogen refuelling stations likely to be co-located with existing petrol stations and clustered in metropolitan areas.[101]

3.2.3 Hydrogen as an industrial feedstock

The chemical industry is by far the largest consumer of hydrogen today, using in excess of 90% of global production.[102] About half of all hydrogen is used to produce ammonia. Demand for hydrogen from existing industries such as these is expected to grow 25% by 2050. New industries, such as making low-carbon synthetic fuels, could significantly increase demand for hydrogen as a feedstock.[102]

The current and potential future uses of hydrogen as a feedstock in Australia are discussed further below.

Ammonia

Ammonia (NH_3) is a compound of hydrogen and nitrogen. More than 85% of ammonia produced globally is used to make fertilisers. It is also used as a cleaning agent, a refrigerant, as a fuel or to be converted into explosives. [103]

Australia now accounts for about 1% of global ammonia production and 1.8% of global ammonia exports.[104,105] The expected increase in demand for low-emissions commodities presents the opportunity to increase our share of the export market for ammonia and related products made from low-emissions hydrogen.

As well as being a valuable commodity in its own right, ammonia is a means to export hydrogen, as discussed in Section 3.1.2.

100 *Green Car Congress*, "S Korea to invest $2.3b in hydrogen fuel cell vehicle industrial ecosystem over next 5 years", 25 June 2018, accessed July 12, 2018, http://www.greencarcongress.com/2018/06/20180625-korea.html
101 International Council on Clean Transportation, *Developing hydrogen fuelling infrastructure for fuel cell vehicles: A status update*, October 2017, accessed July 13, 2018, https://www.theicct.org/sites/default/files/publications/Hydrogen-infrastructure-status-update_ICCT-briefing_04102017_vF.pdf
102 Hydrogen Council, *Hydrogen scaling up: A sustainable pathway for the global energy transition*, 2017.
103 "Hydrogen", The Essential Chemical Industry, accessed July 13, 2018, http://www.essentialchemicalindustry.org/chemicals/hydrogen.html
104 Venkat Pattabathula and Jim Richardson, "Introduction to Ammonia Production", *CEP Magazine*, September 2016.
105 CSIRO, *National Hydrogen Roadmap*, 2018.

Refineries and petrochemicals

Hydrogen is a critical ingredient for cleaning and transforming crude oil into valuable fuel and chemical products. There is very little demand for clean hydrogen in oil refining as most of the required hydrogen is produced from the crude oil earlier in the process.

There are, however, opportunities in the processing of biological feedstocks, or bio-crude, for use as fuels and chemicals. Hydrogen requirements are higher for bio-crude refining than for oil refining.

Synthetic fuels and chemicals

Hydrogen can be converted to fuels and chemicals, such as methanol, through reaction with CO_2. This is generally known as 'CO_2 utilisation'.

Methanol (CH_3OH) is a particularly versatile chemical from which many more chemicals can be derived. Methanol is also an energy carrier, although its use for energy results in CO_2 emissions. It is no longer produced in Australia, with the last plant, in Laverton, Victoria, closing in 2017 due to the surging cost of natural gas.

Low-emissions methanol can be made using low-emissions hydrogen combined with CO_2 from a biomass source, CO_2 captured from the air or CO_2 that would otherwise be vented into the atmosphere. Capturing atmospheric CO_2 is currently financially prohibitive and high-concentrations streams from biomass or other sources are not easily available in Australia.

Internationally, several projects demonstrating CO_2 utilisation are already operating, and others are planned.

In Germany, Audi is using hydrogen made from wind-powered electrolysis and waste CO_2 from a nearby biogas plant to produce synthetic natural gas. This gas is then used to supply natural gas vehicles, in effect making them zero emissions.[106] In Norway, diesel fuel is being produced from hydrogen generated through wind-powered electrolysis and CO_2, some of which is directly captured from the atmosphere.[107]

Iron and steel production

Coal is currently used in iron and steel production both for heat and as a chemical feedstock for converting iron ore into iron. Hydrogen could carry out both of these functions, eliminating most of the CO_2 emissions from using coal. A small amount of coal would still be required to make steel because steel is an alloy of iron and carbon.

In Sweden, the HYBRIT project aims to produce near-zero-emissions steel by 2035 through the use of renewable hydrogen.[108] Producing iron and steel for export from Australian iron ore and hydrogen presents a similar long-term opportunity.

Other industries

A range of industries use hydrogen in small quantities. It is essential for semiconductor fabrication. It is used in processes where very high temperatures and very clean burning is required, such as making glass. It is used in the food industry to transform plant oils into margarines and semi-solid fats. Australian margarine manufacturers will need more of it as their industry grows an expected 23.5% to $1.3 billion by 2030 to meet demand from local and Asian markets.[109]

106 "Power to gas plant", Audi, accessed June 19, 2018, https://www.audi.com.au/au/web/en/models/layer/technology/g-tron/power-to-gas-plant.html
107 *Renewable Energy Magazine,* "First commercial 'Blue Crude' plant being planned in Norway", 11 July 2017, accessed June 20, 2018, https://www.renewableenergymagazine.com/panorama/first-commercial-a-blue-crudea--plant-20170711
108 "HYBRIT – Toward fossil-free steel", SSAB, accessed June 27, 2018, https://www.ssab.com/company/sustainability/sustainable-operations/hybrit
109 IBISWorld, *Cooking Oil and Margarine Manufacturing – Australia Market Research Report*, November 2017.

3.3 A resilient energy system

Australia's electricity supply increasingly relies on renewable sources such as solar PV and wind. The variable nature of this generation requires greater system flexibility to ensure the supply of electricity continues to match demand at all times. This can be achieved by the inclusion of flexible loads and dispatchable generation systems. Hydrogen technologies are well-suited for both of these roles (see Figure 10).

3.3.1 Hydrogen as a flexible load

For many electrical loads such as lighting or medical equipment there is little or no flexibility to ramp them up and down or delay their use in response to market signals. Some other loads, such as pool pumps, don't need to run at a particular time and can be set to run when renewable generation is plentiful and wholesale prices are low. Loads such as these can respond to market signals, helping to reduce the cost of balancing supply and demand in the system.

Electricity system reliability

Electrolysers for hydrogen production can be operated flexibly since the hydrogen is stored for later use. Electrolysers used to produce hydrogen can ramp their operations up and down to match the availability of electricity. The operator of the electrolyser can therefore maximise profits by producing hydrogen at times of excess generation or when electricity is cheap. As flexible and controllable loads, electrolysers will help to maintain system reliability and potentially improve the economics of renewable energy generation. Electrolysers can be deployed in large centralised facilities or as smaller distributed local loads.

Electrolysers can be located close to generation sources, such as solar and wind farms, and potentially used in conjunction with other forms of storage, such as batteries or pumped hydro, to smooth output to the grid, mitigate renewable energy curtailment and improve project economics.[110]

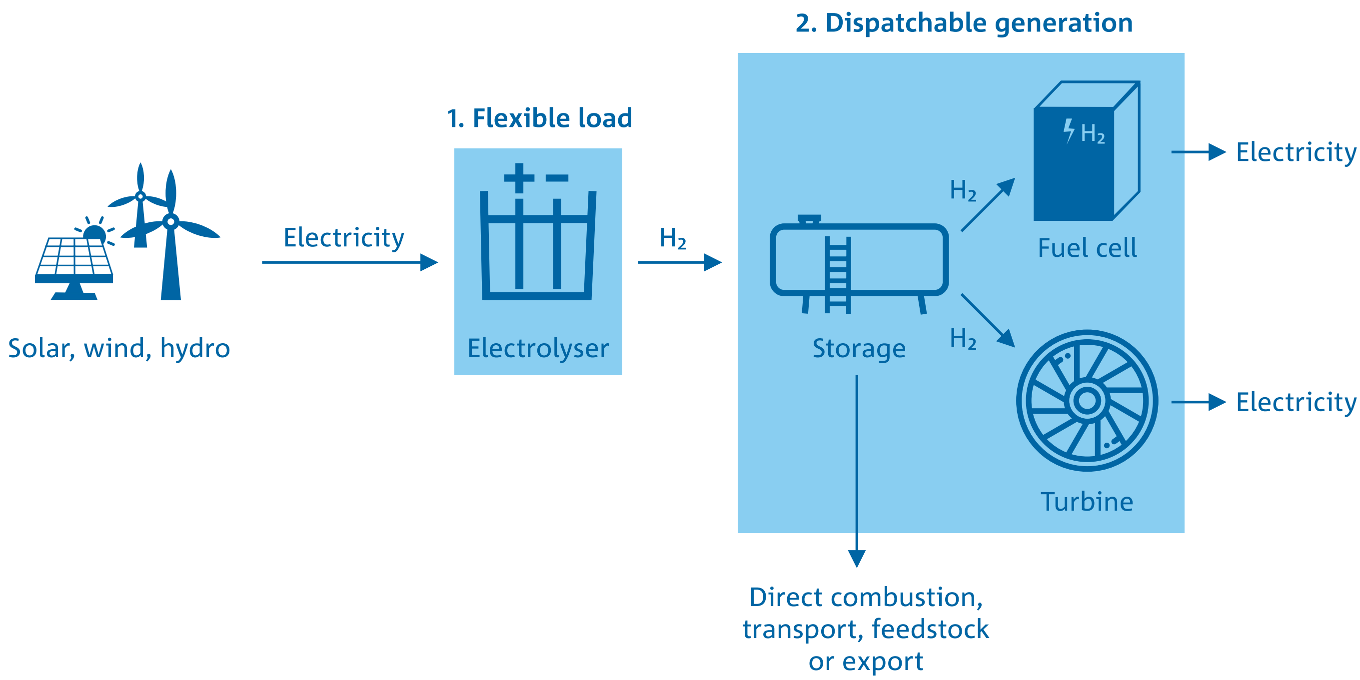


Figure 10: Roles for Hydrogen in the electricity system.

110 Curtailment may be caused by network constraints or other limits imposed on variable renewable generation.

Electricity system security

Polymer electrolyte membrane (PEM) electrolysers are particularly well-suited for use as flexible loads since they can be ramped up and down in less than a second.[111] This introduces the possibility for them to be used to provide demand-side frequency control ancillary services and fast frequency response, contributing to system security and earning additional revenue.

It is estimated the cost of providing these services from fuel cells has the potential by 2030 to be similar to that provided from batteries.[112]

3.3.2 Hydrogen for dispatchable generation

Hydrogen produced by electrolysis can be stored and used to produce electricity when needed using fuel cells or turbines. PEM fuel cells are again likely to be the most widely used systems due to their larger global market, wide range of applications and faster start-up times.[113] The world's largest fuel cell electricity generator, in South Korea, is rated at 59 megawatts. Since hydrogen can be stored economically for long periods, it could be used to store excess energy generated in summer for use in winter (i.e., seasonal storage).

Using hydrogen to drive turbine generators is currently a less mature technology than fuel cells. Although gas mixtures with a high proportion of hydrogen have been demonstrated, the high operating temperatures required for high efficiency lead to unwanted nitrogen oxide emissions.[114] If the challenges can be overcome, hydrogen (or ammonia) turbines have excellent potential for large-scale systems (>100 MW). There is the potential to repurpose existing gas turbines, which would reduce capital costs.

The main competing options for storing and dispatching renewable electricity are batteries and pumped hydro.[115] The three storage technologies have different costs and characteristics that make each suitable for different applications (see Table 2). Key factors affecting the economics of storage are the round-trip efficiency[116] and the capital costs of the initial conversion, storage and electricity production components.

111 Current PEM electrolysers can ramp 10% of their rating per second, meaning 10 seconds to 100% load.
112 CSIRO, *National Hydrogen Roadmap*, 2018.
113 CSIRO, *National Hydrogen Roadmap*, 2018.
114 *Modern Power Systems*, "Fusina combined cycle project: planning to run on pure hydrogen", 1 September 2008, accessed July 13, 2018, http://www.modernpowersystems.com/features/featurefusina-combined-cycle-project-planning-to-run-on-pure-hydrogen/
115 Another potential method for large-scale storage of electricity is compressed air. Energy can also be stored without first producing electricity, for instance using concentrating solar thermal and bioenergy. Concentrating solar thermal systems are expected to be economic with storage times of several hours. Biomass used for bioenergy can be cost-effectively stored for months, similar to hydrogen, but its potential to scale is limited by feedstock availability.
116 The round-trip efficiency measures how much of the energy used to charge the device could be extracted again.

TABLE 2: COMPARISON OF STORAGE TECHNOLOGIES.

STORAGE TECHNOLOGY	ROUND-TRIP EFFICIENCY	COSTS	POTENTIAL APPLICATIONS
Hydrogen	Approx 35%[118]	• High cost of initial conversion technology (electrolysers). • Low cost of storage allows generation duration to be economically scaled. • Moderate to high cost of power output technology (turbines and fuel cells). • Potential for cost reductions or efficiency improvement.	• Applications requiring low power-to-energy ratios and long-term storage. • Energy generation at peak output for days to weeks.
Batteries	Approx 90%[119]	• Low cost of initial conversion (power electronics). • High cost of storage (battery cells) with slim economic benefit of scaling. • Costs rapidly falling. • Viable at very small sizes. • Potential for modular installation.	• Applications where storage is highly utilised, e.g., frequently charged and discharged, or requiring fast response. • Other high power-to-energy ratio applications. • Self-discharge occurs during long-term storage. • Energy generation at peak output for many hours.
Pumped hydro[120]	Approx 75%[121]	• Moderate cost of initial conversion and electricity production (pumps and turbines). • Low cost of storage (dam size) allows generation duration to be economically scaled. • Viable at larger sizes. • Mature technology thus relatively little cost-reduction potential.	• Applications requiring low power-to-energy ratios. • Long-term storage. • Energy generation at peak output from multiple hours to days.

117 Based on current costs.

118 Electrolysis and hydrogen storage has a combined efficiency of 56-73%. Hydrogen gas turbines are predicted to have an efficiency of about 57%, and turbines using hydrogen blended with natural gas have an efficiency of 63%. See Paolo Chiesa et al, "Using Hydrogen as Gas Turbine Fuel", *Journal of Engineering for Gas Turbines and Power*, vol. 127, issue 1, January 2005, and *FuelCellsWorks*, "MHPS Successfully Tests Large-Scale High-Efficiency Gas Turbine Fuelled by 30% Hydrogen Mix", 25 January 2018, accessed July 13, 2018, https://fuelcellsworks.com/news/mhps-successfully-tests-large-scale-high-efficiency-gas-turbine-fueled-by-30-hydrogen-mix. Fuel cells are typically 40-60% efficient depending on the fuel cell type. See "Fuel Cells Fact Sheet", US Department of Energy, accessed July 13, 2018, https://www.energy.gov/sites/prod/files/2015/11/f27/fcto_fuel_cells_fact_sheet.pdf.

119 For Li-ion batteries including power conversion from AC to DC when charging and back again on discharge.

120 For this comparison, only off-river pumped hydro is considered.

121 Marsden Jacobs and Associates, *Snowy 2.0 Feasibility Report*, 2017.

Using hydrogen to store electricity involves high-cost initial conversion (electrolysers) and high-cost reconversion to electricity (fuel cells and turbines), making it an expensive option for short time scales. Storing the hydrogen using underground formations can be very cheap, however, meaning it is potentially cost-effective for long-term large-scale storage (multiple days to months).
Future cost reductions of electrolysers, fuel cells and turbines are expected. Further cost reductions for solar PV and wind will also help mitigate the cost impact of the relatively low round-trip efficiency.

If hydrogen can be produced at a cost of less than $2/kg ($16.67 per GJ),[122] it could provide a cost-competitive alternative to natural gas turbines for dispatchable generation. Higher hydrogen prices may also be competitive should natural gas supply risk and carbon price risk be factored in.[123]

Uptake of hydrogen technology is a function of both the cost of hydrogen generation and the benefits to the system versus competing technologies. Hydrogen electricity technologies are expected to be economically viable earlier in remote-area power systems than in larger metropolitan systems. In remote systems, hydrogen produced on-site could be used to back up solar photovoltaics or wind, replacing diesel that is expensive to supply to distant off-grid locations.

3.3.3 Hydrogen for fuel diversification

Australia is increasingly reliant on imports for its liquid fuels. Australia's domestic crude oil production declined by 23% in the decade to 2016, by which time Australia imported 67% of its oil, and 91% of its oil for transport.[124] Import of oil products is expected to grow by 3.2% a year to 2021-22.[125] Being heavily reliant on supplies from the Middle East makes Australia vulnerable to potential supply disruptions and to unexpected changes in demand from other customers in Asia.

Australia's 2011 National Energy Security Assessment highlighted the security benefits of increased energy diversity.[126] As discussed in Section 3.2.2, hydrogen fuel cell electric vehicles could play an important role in diversifying fuel types and reducing our reliance on imported liquid fuels for transport.

122 Required price point for hydrogen to be realistically competitive in this sector: CSIRO, *National Hydrogen Roadmap*, 2018.
123 CSIRO, *National Hydrogen Roadmap.* 2018.
124 International Energy Agency, *Energy policies of IEA countries: Australia 2018 Review*, February 2018, accessed July 13, 2018, www.iea.org/publications/freepublications/publication/EnergyPoliciesofIEACountriesAustralia2018Review.pdf
125 Senate Standing Committees on Rural and Regional Affairs and Transport, *Australia's transport energy resilience and sustainability*, June 2015, accessed July 13, 2018, https://www.aph.gov.au/Parliamentary_Business/Committees/Senate/Rural_and_Regional_Affairs_and_Transport/Transport_energy_resilience/Report/c02
126 Department of Resources, Energy and Tourism, *National Energy Security Assessment 2011*, December 2011, accessed July 13, 2018, https://www.energy.gov.au/government-priorities/energy-security/energy-security-assessments

4 Capturing the opportunity: the role of government

Making Australia the world's premium hydrogen supplier will – and should – be the task of business. However, there are aspects of creating an industry that only governments can manage. The community expects a hydrogen industry to be properly regulated, whether for safety and planning or for trading and pricing. Governments are also a trusted source of information and should commission studies to inform both the public and industry. Support for research and development is important, both now and as the industry develops, to drive down costs, improve efficiencies and address environmental concerns. Finally, governments should consider a national hydrogen strategy to accelerate progress and maximise economic benefits, while maintaining and deepening public engagement in hydrogen industry development.

4.1 Community attitudes and expectations of government

Effective community engagement and societal acceptance will be important factors to successfully develop new hydrogen technologies and related infrastructure projects. Trust is essential for earning a social licence to operate and ultimate acceptance of projects. It will be built through open and transparent decision-making, responding to community concerns, ensuring benefits are shared equitably, and putting in place appropriate governance structures.[127] Engaging with the community as early as possible and providing relevant information is important to build trust in proposed hydrogen projects.[128,129]

Australians already accept the risks associated with using natural gas, petrol and diesel (all combustible fuels) in their homes, businesses and vehicles. Although hydrogen has different properties to currently used fuels, these properties can be managed to ensure its risks are no greater than other fuels. However, while experts are confident in the ability to manage the risks, societal responses can vary markedly and are not always based on the properties of the fuel source alone.

Government and industry will need to work together to ensure that early and ongoing communication and engagement with the broader public is undertaken in an effective and fit-for-purpose manner. The recently announced Future Fuels Cooperative Research Centre has a goal to explore how to earn a social licence for hydrogen production, transportation and storage infrastructure, through engagement with communities affected both directly and indirectly by projects. Aspects of the Cooperative Research Centre's work program specifically address how best to engage with the community to support informed decision-making.

127 Airong Zhang et al, "Understanding the social licence to operate of mining at the national scale: a comparative study of Australia, China and Chile", *Journal of Cleaner Production*, vol. 108, December 2015.
128 Peter Achterberg, "The changing face of public support for hydrogen technology explaining declining support among the Dutch (2008-2013)", *International Journal of Hydrogen Energy,* vol. 39, issue 33, 11 November 2014.
129 Rob Flynn et al, "Environmental citizenship and public attitudes to hydrogen energy technologies", *Environmental Politics,* vol. 17, no. 5, November 2008.

What do the Australian public think of hydrogen? Results from early research

In June 2018, the University of Queensland ran 10 focus groups, in Adelaide (3), Whyalla (2), Melbourne (3) and Traralgon (2). In total, 92 participants (55 female, 37 male) of mixed ages (20 to 76 years with an average age of 44) and employment status attended. Key findings from this study included:

Participants were cautiously positive, as long as their concerns were addressed: Initial knowledge of hydrogen as an energy carrier was generally low, and initial concerns were mainly expressed around the volatility and flammable nature of the gas. Support grew when participants heard and saw examples from other countries already using hydrogen or moving in that direction. Participants responded positively to the potential to use hydrogen for various applications including for export, transport, home use and electricity storage, on the proviso that issues around safety, cost, convenience and environmental concerns were addressed.

"It certainly shows all the hallmarks of something that is worthwhile investing in, as long as the groundwork is put in to implement it across the board evenly and safely." [FG10]

The environment must be considered: Participants expressed mixed feelings about producing hydrogen from fossil fuels with CCS rather than renewables, with cost and environmental impacts being critical to acceptance of either. Participants also expressed concern about exporting Australia's limited water resources through the manufacture and export of hydrogen.

There could be economic benefits, but these need to be shared fairly: Participants saw benefits arising from an export market but felt strongly that export should not take precedence over domestic supply. Any transition to hydrogen for domestic use, either in the home or for transport, would need to be comparable with current costs. Participants recognised local production would bring regional benefits through increased opportunities for jobs and services.

"Sounds like it is a really great opportunity, doesn't it… Get the science right, and make sure the country benefits. Reliability of electricity supply and cost is crucial." [FG1]

Government should lead in collaboration with industry and researchers: Expectations for government included ensuring adequate regulations were in place, providing funding for R&D, as well as incentives to encourage individuals to participate in the transition. A bipartisan approach was seen as essential.

People want to know more, especially about the transition: Participants had many questions and were keen for more information about hydrogen through independent, open and transparent communication and engagement. Participants felt that while people tend to be cautious of the unknown, with education and demonstrations of the use of hydrogen, the public would become accustomed to hydrogen, similar to the switch from town gas in the 1960s. They were interested to understand what changes would have to be made within homes, particularly in relation to appliances, as well as how much choice individuals would have to be part of a hydrogen community if one was rolled out in their area.

4.2 Commissioning studies

4.2.1 Safety

As with the introduction of any new technology, there are a number of social-acceptance issues in the field of hydrogen and fuel cell technologies that will have to be investigated through government-commissioned studies. Public confidence in domestic hydrogen industries conforming to international safety standards – both behind the meter and when hydrogen is being stored and distributed at scale – and perceptions of the cost advantage over fossil fuels are likely to significantly influence support for the development of hydrogen industries in Australia. Understanding public perceptions and attitudes to these issues will inform the development of a national hydrogen strategy. Safety studies can also consider the extent to which Australia should adopt international standards as they evolve, and the extent to which bespoke standards will be needed to suit our national needs.

4.2.2 Planning

An important first step in developing a national hydrogen strategy will be to map the need for regulatory reform at federal, state and local levels. This will help all levels of government to work in partnership to address barriers to market by understanding how existing regulations affect hydrogen and hydrogen infrastructure, and identify where further regulation or deregulation is necessary to support market development. This may include regulations to support hydrogen assets to realise their full commercial value, or technical regulations to ensure design, construction and operation of hydrogen infrastructure meet appropriate safety and environmental standards. Urban planning, and planning and development consents more generally, may also need to be considered.

4.2.3 Economics

Developing an understanding of the resource economics of hydrogen exports will be crucial to inform the business case for domestic projects and a broader export industry. ARENA is exploring aspects of this, but building a robust picture of this potential market and Australia's place in it will be an iterative process. Globally there is limited project cost data available for renewable hydrogen projects. Moreover, while some demand assumptions may be made based on announced national polices and existing trading relationships between economies, many of these will need to change substantially to deliver the long-term ambition of international agreements.

4.3 Developing a national strategy

Other countries are moving to develop national strategies on hydrogen, Japan being the most prominent example. Japan's strategy is squarely focused on using imported hydrogen to reduce its dependence on imported fossil fuels. It has clear price targets for the imported hydrogen and numeric targets for the introduction of vehicles, refuelling stations and electricity generation.

Australia, by contrast, has a number of hydrogen-related activities under way (see Chapter 5) but the approach is fragmented and uncoordinated. A national hydrogen strategy for Australia could draw these and future activities together to accelerate progress and maximise economic benefits, while maintaining and deepening public acceptance.

Building on the above studies, a national strategy could focus on establishing Australia as the world's leading exporter. Other major components of a national strategy should include prioritising new domestic markets, and a timeline for supporting domestic applications. A strategy should also establish governance and leadership for policy and delivery, including how to draw together work already under way.

4.3.1 Positioning Australia to capture the hydrogen export market

Australia is well-positioned to capture emerging large scale markets for hydrogen in Asia. We are already a trusted supplier of energy resources to many countries in the region, supplying one-fifth of South Korea's LNG imports and nearly half of Japan's.

However, competition to supply hydrogen to Japan is already emerging from Norway, Brunei and Saudi Arabia.

To make the most of the opportunities in Asian markets, Australia needs to prove the supply chain economically and technically; invest in bringing down production and logistics costs; and work with other countries to put the market infrastructure in place so that hydrogen can emerge as a tradeable bulk commodity.

An example of where government agencies have anticipated the regulatory requirements that will facilitate the development of the hydrogen export industry is in international shipping. In 2016 the International Maritime Organisation (IMO) approved interim recommendations to safely transport liquefied hydrogen in bulk over international waters, a result of the integrated work between the Australian Maritime Safety Authority (AMSA) and the Japanese Ministry of Land, Infrastructure, Transportation and Tourism (MLIT).[130]

The Hydrogen Energy Supply Chain project in Victoria (see Section 5.1) will contribute to proving supply chain logistics, including moving hydrogen from points of production to export terminals, compression and liquefaction, bulk transportation and offloading. A national strategy could identify other demonstration projects to evaluate the economics and technical feasibility of using other hydrogen carriers such as ammonia. It could also identify demonstration projects that improve technical feasibility and investigate ways to continue to reduce the costs of production.

130 https://www.amsa.gov.au/news-community/news-and-media-releases/australia-and-japan-develop-safety-standards-shipping-liquid

For a commercial market in bulk hydrogen to emerge across Asia, market infrastructure will be required. Establishing trading hubs would allow both producers and consumers to invest efficiently and manage risk, through measures such as hub pricing, demand visibility, futures contracts and other financial instruments. Transparency of data and information (including hydrogen prices and volumes) along the value chain will also stimulate innovation.

A national strategy could actively encourage establishment of the underpinning market infrastructure and government-to-government agreements required to secure Australia's position as a leading producer.

4.3.2 Enabling progressive hydrogen use in domestic gas networks

Progressively adding small amounts of hydrogen to domestic gas networks would be one way to gradually build local demand and begin driving down production costs as manufacturing scales up. Starting with 2% by volume and gradually moving to 10% over a period of years would be achievable with no impact on distribution infrastructure or appliances, and a low impact on prices. How and when to make this transition should be determined in close consultation with stakeholders. Nevertheless, a recent review of relevant legislation and market rules by Energy Networks Australia shows there are no regulations that prohibit the injection of hydrogen at low concentrations into existing gas infrastructure.

Should Australia progress with plans to convert to 100% hydrogen, some legislative and regulatory instruments would need amendment. These are:

National Gas Law: Currently applies to natural gas only, as defined as a gas that is predominantly hydrocarbon-based. Given hydrogen has no carbon, the National Gas Law would not apply to gas assets that transport 100% hydrogen. Before conversion to 100% hydrogen, the definition of "natural gas" will need to be amended.

Gas technical specification: The Australian Standard 4564 "Specification for general purpose natural gas" provides a specification for natural gas used in Australia in the gas industry for contractual and quality purposes. This standard is applicable only to natural gas. A new technical specification will need to be developed for 100% hydrogen.

State-based regulations: These regulations specify the requirements for gas composition and safety. Any injection of hydrogen into networks will need to comply with these safety requirements. As such, these regulations may need to be updated to allow for and reflect 100% hydrogen.

Household appliances: Current regulations regarding household gas appliances (such as cooktops, gas heating and hot water services) only apply to natural gas, propane and LPG appliances. Should Australia commence converting gas infrastructure to 100% hydrogen, appliance regulations will need to be amended.

4.3.3 Establishing frameworks for hydrogen vehicles

A national strategy could play a key role in bringing hydrogen vehicles into the Australian transport sector. Existing vehicle regulations around safety and performance standards focus on vehicles with internal combustion engines. A national strategy could set out a roadmap for adjusting regulations over time to accommodate hydrogen vehicles.

Refuelling infrastructure will be key to widespread adoption of hydrogen vehicles, whether for the light, heavy, or industrial markets. An important part of any national strategy on hydrogen should be to examine likely refuelling infrastructure needs under different scenarios and examine ways in which this can be financed. Setting out a plan for refuelling infrastructure will allow business and governments to work together to ensure a smooth rollout.

4.3.4 Evaluating contribution to energy systems

Under a national hydrogen strategy, government can work with industry to evaluate and implement best practices for using renewable hydrogen to support the energy system. Energy storage will be crucial in the transformation of the Australian electricity network. Without long-term storage, additional renewable capacity above a certain threshold will not be efficient to build. With its ability to provide seasonal energy storage, rapid load shifting for frequency services and response to variable generation to smooth out the peaks and troughs in renewable energy generation, renewable hydrogen production can help the network support a higher share of renewables than otherwise feasible.

4.3.5 Facilitating adoption in industrial processes

Beyond decarbonising the electricity sector, a more difficult frontier is industrial emissions where, to date, few options have existed for processes that use hydrocarbons as feedstock. As set out in Chapter 3, there are opportunities to use renewable hydrogen in high-temperature manufacturing (such as steel making) and in chemicals, plastics and fertiliser production. A national strategy could explore the potential of these opportunities in more detail, including the possibility of future expansion of these industries to take advantage of Australia producing large amounts of renewable hydrogen. A national strategy could also map the need for pilot projects as practical demonstrations.

4.3.6 Governance

A national strategy could investigate governance structures for an Australian hydrogen industry. As hydrogen has multiple uses in multiple sectors, and can be consumed domestically as well as exported, governance is likely to involve multiple agencies at multiple levels of government. Governance could focus on achieving end-to-end oversight of the hydrogen supply chain, carried out co-operatively and transparently between business, industry, technical experts, community representatives and all levels of government.

As can be seen from the renewable energy market, disruptive change often arrives faster and at lower cost than expected. Hydrogen will be no different. Policy settings for hydrogen will therefore need to be flexible and resilient, able to respond quickly to changing markets while providing sufficient certainty.

4.4 Supporting research, development, demonstration and pre-commercial deployment

For any hydrogen policy goals around hydrogen to be achieved, further technology improvements as well as mass-market volumes are needed to drive hydrogen cost-competitiveness in the broader energy system. If hydrogen is to become an internationally traded commodity, similar to LNG, supply chains will need to be demonstrated. R&D will be required across production, storage and transport to reduce the delivered cost.

Australia has a suite of government programs to support R&D and help emerging technologies to make the transition from demonstration to commercial implementation. Within this ecosystem there are a number of programs specifically targeting hydrogen innovation, but market development programs are under-represented. Active markets will reinforce research and development activities, but until these are established Australian hydrogen deployment will not proceed past demonstration stage.

A number of potential aspects for demonstration projects are outlined above. The national strategy could outline a co-ordinated approach to R&D and demonstration projects, and facilitate sharing of outcomes across industry to drive further innovation and learning.

Driving innovation also requires technology and market risk-sharing between industry and government, recognising that both have something to gain and both need to innovate as a response to disruption. Government and business alike need to recognise and respond quickly to hydrogen’s potential to augment or disrupt many existing sectors.

4.5 Timeline for export and domestic applications

The biggest near-term opportunity for hydrogen production is export. Growth will be limited by the rate at which large customers such as Japan and South Korea ramp up their demand, Australia's ability to ramp up production, and competition from other countries. It is reasonable to assume the lead-time to develop this opportunity might be similar to that for the now mature LNG industry (see box below).

Adding hydrogen gas to domestic natural gas supply at up to 10% by volume can be done without requiring changes to appliances, pipes or meters (although metering algorithms will need to be changed to account for hydrogen's different energy density). This low-impact approach will enable the industry to build experience and capability at a manageable rate. Small-scale trials by AGIG in South Australia and ATCO in Western Australia have already been announced (see Section 5.1). 100% natural gas substitution will commence at scale when safety studies have been completed, experience has been developed at the 10% substitution level, and local, state or territory and Commonwealth governments agree on the benefits. A small-scale trial is planned for the ATCO demonstration project at Jandakot.

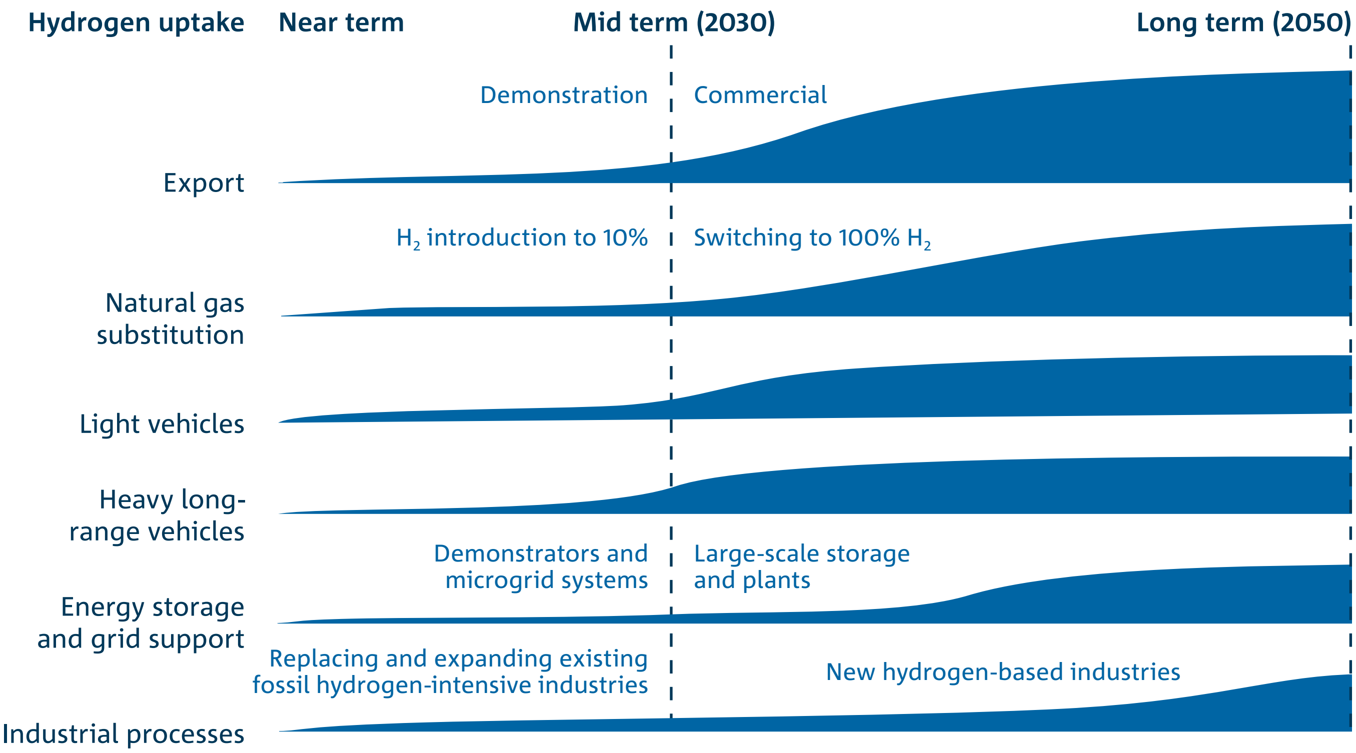


Figure 11: Hypothetical trajectories for hydrogen uptake in Australia (not based on modelling).

Light vehicles will be successful if manufacturers produce sufficient models and if refuelling stations are built in adequate numbers. The competition in this space will be from battery electric vehicles.

Long-haul vehicles will be available from international manufacturers in the next few years. They are already on trial in Europe. Given the vehicles will have very long range and only use a limited set of roads, they can be serviced with a small number of refuelling stations. Fleet vehicles also benefit from operating from a limited number of bases, at which refuelling can be located. Local fleet vehicle trials in Australia have been announced, including 20 passenger vehicles for the ACT Government and 18 garbage trucks for Moreland City Council in Victoria.

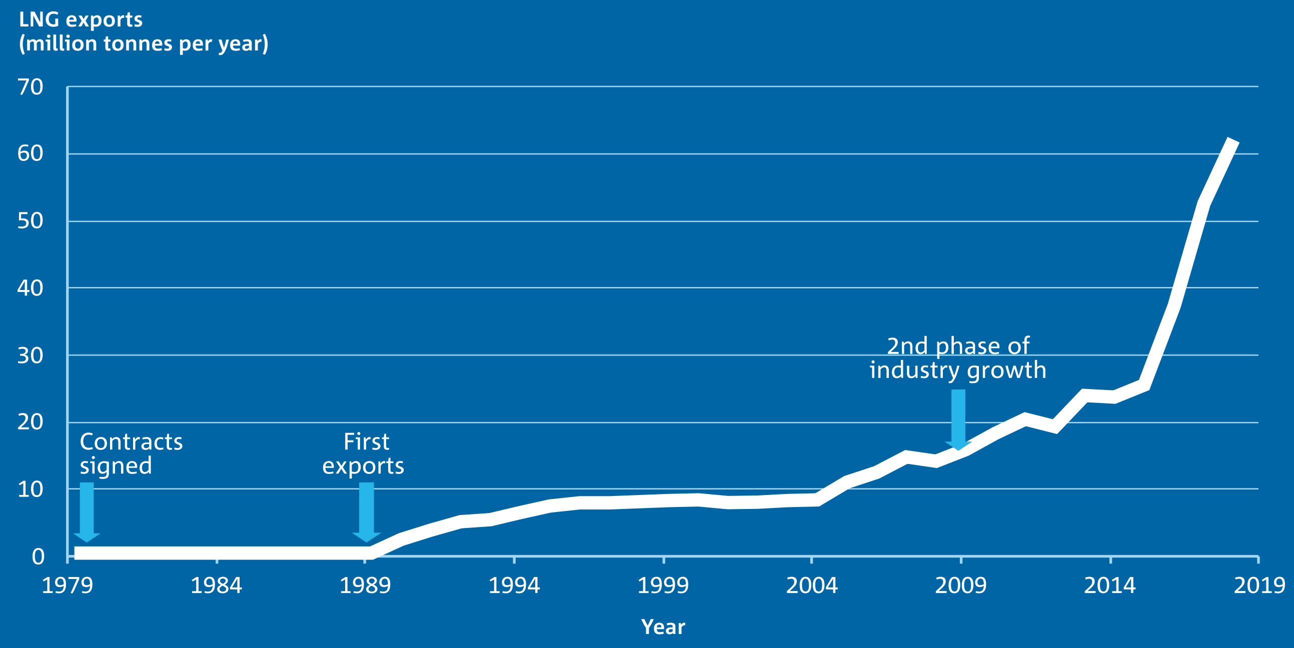
Energy storage will depend on the production price of hydrogen falling to a level where the low round-trip efficiency is not a stumbling block, or if hydrogen stored for use in heating and transport is available for generation when electricity prices are high.

Flexible load benefits will accrue as soon as electrolysers are deployed at substantial scale. A number of trials at the megawatt level are in development.

Industrial processes are long-term because they will depend on the hydrogen production price falling to be comparable to natural gas prices. These applications will be needed if countries are to achieve deeper decarbonisation after the lower hanging fruit of the electricity, transport and heating sectors have been picked.

Creating an energy export industry for Australia: the LNG example

Australia's LNG industry offers an example of the possible time scale for creating a new hydrogen export industry.



Timeline of LNG development

1963	Woodside granted North West Shelf oil and gas tenements.
1967	Federal government introduces the Petroleum (Submerged Lands) Act.
1979	Western Australian government underwrites the development of the Carnarvon Basin and Australia's future LNG export industry by entering into long-term take-or-pay contracts from the North West Shelf Venture (NWSV).
1981	NWSV signs formal LNG sales agreement with eight Japanese gas and power companies.
1984	First domestic gas delivered to WA.
1989	First export of LNG from Australia (NWSV).
1995	Discovery of the Bayu-Undan field north-west of the Northern Territory.
1999	Commonwealth formally establishes the annual Offshore Petroleum Exploration Acreage Release.
2000	Queensland government announces gas scheme that significantly boosts the CSG industry.
2002	Agreement for NWSV to supply LNG to China for 25 years and establishment of the Australia China Natural Gas Technology Partnership Fund.
2006	First LNG exports from Northern Territory.
2009	Blueprint for Queensland's LNG Industry released.
2015	First LNG exports from Queensland.
2018	Western Australian government announces plan to establish an LNG Jobs Taskforce.

5 Activity snapshot

5.1 Australian activity

National

- Hydrogen Mobility Australia (HMA), established in 2017, brings together vehicle makers, energy companies, infrastructure providers, research organisations and government officials. Its aim is to accelerate the commercialisation of hydrogen and fuel cell technologies for transportation in Australia, including through the delivery of pilot and demonstration infrastructure projects.
- Future Fuels Cooperative Research Centre (FFCRC) announced in April 2018, has secured more than $90 million in funding (including $26.5 million from the federal government and $8 million from gas network businesses) to undertake research and development to help transition Australia's energy infrastructure to low-carbon fuels such as hydrogen and biogas.
- CSIRO's 'Hydrogen Energy Systems' Future Science Platform is focused on innovation opportunities across the hydrogen energy value chain. It will invest in science that underpins such innovation with the potential to reinvent old industries and create new ones for Australia.
- CSIRO's *National Hydrogen Roadmap for Australia* (2018) outlines global and local trends, opportunities for an Australian hydrogen industry, and technical barriers to realising these opportunities.
- ARENA's Investment Plan published in May 2017 identifies 'Exporting renewable energy' as one of four investment priorities, with hydrogen being the major export focus. ARENA has allocated $20 million in its Hydrogen R&D Funding Round launched in December 2017 for projects to develop renewable energy export supply chains based on hydrogen.
- The Australian Research Council (ARC) Centre of Excellence for Electromaterials Science has $25 million funding for materials research, much of which has applications in the hydrogen supply chain.
- The Australian Association for Hydrogen Energy (AAHE) was established after the 2008 publication of the federal government's *Hydrogen Roadmap* to promote the use of hydrogen as an energy carrier, its integration in the Australian energy economy, and the development and deployment of hydrogen energy technologies.

Australian Capital Territory

- To support its emissions-free vehicles plan covering all newly leased government passenger vehicles by 2021, the ACT government will buy 20 hydrogen fuel cell vehicles. Neoen and partners have committed to building a 1.25 MW electrolyser to produce hydrogen from renewable energy, and a refuelling station.

New South Wales

- Jemena Gas Networks is exploring a renewable hydrogen pilot project on its network to demonstrate large-scale renewable energy storage and distribution by existing gas pipeline infrastructure.
- Hyundai has installed a hydrogen refuelling station at its Australian head office in Macquarie Park, Sydney.

Northern Territory

- Through its Roadmap to Renewables policy, the Northern Territory government is monitoring progress in technology innovation including hydrogen-based energy generation and transport systems. The NT has significant on-shore gas reserves to support the production of ammonia and hydrogen-based commodities for domestic and international markets.

Queensland

- The Queensland government has committed $750,000 for a feasibility study into producing hydrogen using solar energy from central Queensland and exporting it to Japan via Gladstone.
- ADME Fuels is developing a zero-emissions liquid fuel project using renewable hydrogen and CO_2.
- Southern Oil Refining is developing a project in Gladstone to make hydrogen from biomass for fuel cell power generation and for upgrading bio-crudes as a key enabler of renewable fuels value chains.

South Australia

- The South Australian government's *Hydrogen Roadmap* and *Green Hydrogen Study*, published in September 2017, set out a blueprint to accelerate the state becoming a sustainable producer, consumer and exporter of hydrogen. The state government has since invested more than $15 million in grants and $27.5 million in loans to four green hydrogen projects:
  - Crystal Brook Hydrogen Superhub. Neoen is looking to build a $600 million renewable hydrogen production facility at the 305 MW Crystal Brook Energy Park near Port Pirie. The proposed 50 MW hydrogen plant would make Crystal Brook the largest co-located wind, solar, battery and hydrogen production facility in the world, producing about 7,000 tonnes of hydrogen a year.
  - Hydrogen Park of South Australia. Australian Gas Infrastructure Group (AGIG) is investing in an $11.4 million renewable hydrogen demonstration project at the Tonsley Innovation District. The project comprises a 1.25 MW electrolyser connected to the electricity grid, and hydrogen can be injected into the local gas network. AGIG is also leading efforts to establish a National Hydrogen Centre of Excellence at Tonsley.
  - Port Lincoln hydrogen power plant. Hydrogen Utility is developing a 30 MW electrolysis project to make renewable hydrogen and ammonia. The project, valued at more than $117 million, is anticipated to provide balancing services to the national electricity system and fast frequency response support to new solar plants on the Eyre Peninsula. It will make about 300 tonnes of hydrogen a year.
  - Mawson Lakes renewable energy system: The University of South Australia is building a $7.7 million facility incorporating solar power, flow batteries, a hydrogen fuel cell stack and

thermal energy storage at its Mawson Lakes campus. The intention is to create a nationally significant test bed of renewable energy technologies.

- Adelaide will host the International Conference on Hydrogen Safety (HySafe) in September 2019, the first Australian city to do so. Potential flow-on events include a meeting of the International Partnership for Hydrogen and Fuel Cells in the Economy (see Section 5.3).

Tasmania

- The Tasmanian Government maintains a close interest in emerging energy technologies. The Government is also committed to working with key partners to develop a coordinated approach to support the uptake of electric vehicles in Tasmania, including the potential use of fuel cell vehicles.

Victoria

- Hydrogen Energy Supply Chain Pilot Project. A world-first demonstration plant will be built in the Latrobe Valley as part of a $500 million joint Australian-Japanese pilot project to develop technology to produce hydrogen from brown coal then export it as liquefied hydrogen to Japan. Hydrogen gas transported by truck to the Port of Hastings area will be liquefied for transport to Japan in a ship to be developed for this project. The proof-of-concept phase will produce three tonnes a year.
- Renewable hydrogen waste truck trial. With support from the state government, Moreland City Council is deploying a commercial-scale hydrogen refuelling station with a pilot fleet of 18 garbage trucks running on 100% renewable hydrogen.
- Waurn Ponds Smart Energy Partnership. Deakin University and AusNet Services are collaborating in a $30 million project to establish an industrial-scale smart microgrid energy system and integrated research and education platform at the university's Waurn Ponds campus. This project could be expanded to include research of other technologies, such as hydrogen storage, that could lead to hydrogen and electric vehicle integration.

Western Australia

- Yara Australia has announced a pilot project to produce renewable ammonia for export based on hydrogen from solar electrolysis, using the company's existing ammonia production and export infrastructure in the Pilbara.
- Woodside Energy has announced its intention to develop export markets and local refuelling infrastructure based on hydrogen derived from natural gas with CCS and from renewable sources. Woodside has signed a memorandum of understanding with Korea Gas Corp (KOGAS) to collaborate on research and development of hydrogen fuel.
- Clean Energy Innovation Hub. ARENA is providing $1.5 million funding towards a $3.3 million research and development project at ATCO Australia's operations centre in Jandakot. Renewable hydrogen will be produced from on-site solar and then used to generate electricity, fuel a range of gas appliances in a microgrid, and be blended with natural gas in existing pipelines. The project will evaluate the potential for renewable hydrogen to be generated, stored and used at a larger scale.

5.2 Australia's hydrogen R&D capability

Australia's research strengths in hydrogen[131]

- Australia ranks 14th globally in number of publications and 4th in average citations per paper.
- Australia's number of publications has increased by 250% over the past 10 years.
- Australia has a broad research focus covering hydrogen production, engines, ammonia reconversion, vehicles and turbines.

Research institution highlights (non-exhaustive):

- Australian National University: materials chemistry and catalysts to produce hydrogen; solar thermal technologies applicable to hydrogen supply chains.
- CSIRO: development of ammonia membrane cracking technology to separate hydrogen from ammonia; solar thermal technologies and their application in hydrogen supply chains.
- CSIRO's 'Hydrogen Energy Systems' Future Science Platform has commenced projects spanning research across the hydrogen energy value chain, from biological hydrogen generation to large-scale underground storage.
- Curtin University of Technology: hydrogen storage.
- Griffith University (National Hydrogen Materials Reference Facility): materials research aiming to advance hydrogen energy technology.
- Monash University: chemical methods to produce hydrogen and hydrogen carriers.
- Queensland University of Technology: solar and chemical production of hydrogen, and conversion to carriers.
- RMIT University: solar PV-hydrogen systems.
- University of New South Wales: production of hydrogen from solar PV electrolysis and photocatalysis; solid-state hydrogen storage.
- University of Melbourne: Chemical and Electrochemical generation of Hydrogen; hydrogen conversion to fuels and hydrogen storage
- University of Adelaide: Hydrogen production from water, biomass and waste using solar thermal and photocatalysis; hydrogen-derived fuels for industrial processes
- University of Queensland: photo-catalytic and photo-electrochemical processes for solar hydrogen production; spin-off Hydrexia commercialising hydrogen storage technology.
- University of South Australia: solar thermal technologies and their application in hydrogen supply chains.
- University of Sydney: hydrogen from biomass.
- University of Western Australia: hydrogen production through biological processes and from biomass.
- University of Wollongong: spin-off AquaHydrex commercialising novel electrolyser technology.

131 Based on ARENA analysis of published articles for the years 2007-2018, using the categories (search strings) in Australian Academy of Science, *Towards development of an Australian scientific roadmap for the hydrogen economy*, 2008. Data accessed June 28, 2018.

5.3 Australia's engagement with international initiatives

- Mission Innovation Hydrogen Challenge. Australia is be co-leading a new Mission Innovation Challenge, focused on identifying and overcoming technical barriers to the widespread production, transport, storage and use of hydrogen.
- IEA Hydrogen Technology Collaboration Programme (TCP). Australia is participating in two existing tasks related to storage and industrial feedstock, and proposes to participate in two new tasks looking at export supply chains and uses in primary industries. The Australian Association for Hydrogen Energy leads Australia's involvement in this program.
- International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE). Australia is a founding member of the IPHE, which organises and implements international research, development, demonstration and commercial utilisation activities related to hydrogen and fuel cell technologies, and provides a forum to share knowledge on policies, codes and standards.

5.4 Global activity

Internationally the Hydrogen Council is working to foster high-level support for hydrogen technology and its role in the global energy transition. The council, launched in January 2017, comprises chief executives from 39 major energy, transport and manufacturing corporations, including General Motors, Honda, Mitsubishi and Toyota.

Among nations with which Australia has close ties, there is significant interest in hydrogen's essential role in the global energy transition. The following is a select list of notable hydrogen energy programs and projects.

5.4.1 Japan

As outlined in Section 1. 2 (see box: Japanese and South Korean hydrogen strategies), the Ministry of Economy, Trade and Industry (METI) released Japan's *Basic Hydrogen Strategy* in late 2017. The broad-reaching strategy builds on existing efforts to grow domestic hydrogen demand in Japan and to establish import supply chains. Key activities include:

- Uptake of hydrogen fuel cell vehicles. Investment spans vehicle development, manufacture and refuelling infrastructure. Japan is aiming to have 40 thousand vehicles on its roads by 2020, with 200 thousand by 2025 and 800 thousand by 2030.[132]

132 Toyota's Mirai and Honda's Clarity hydrogen fuel cell vehicles are in production; Mazda is developing a hydrogen rotary engine vehicle.

- Subsidies for stationary fuel cells that can provide heat and power to residential homes. The target is 1.4 million installations by 2020 and 5.3 million by 2030.[133]
- Demonstration projects to supply hydrogen to Japan. Two are already under development: the Hydrogen Energy Supply Chain (HESC) pilot project in Victoria, exporting liquefied hydrogen (LH2), and the Advanced Hydrogen Energy Chain Association for Technology Development (AHEAD) project in Brunei, exporting hydrogen as methylcyclohexane (MCH). Projects in Norway and Saudi Arabia are also being explored.[134,135]
- Showcasing hydrogen at the 2020 Tokyo Olympic Games. Hydrogen will be used to power 6,000 passenger vehicles and 50 buses, supported by 35 refuelling stations.[136] Past experience argues that the scheme has the potential to be more than just a demonstration, as the Shinkansen high-speed train system began with the line between Tokyo and Osaka built in time for the 1964 Tokyo Olympics.

5.4.2 South Korea

As outlined in Section 1.2 (see box: Japanese and South Korean hydrogen strategies), the South Korean government has a US$2.33 billion public-private investment plan to accelerate hydrogen fuel cell infrastructure, manufacturing capabilities and technology development. Key hydrogen activities include:

- A target to have 9 thousand hydrogen-powered vehicles on the road by 2020, and as many as 630 thousand by 2030, with subsidies that cover about a third of the price of a new vehicle.[137] There is a target of 310 refuelling stations by 2022.[138]
- The world's largest hydrogen fuel cell power plant, which provides 59 MW of electrical power and district heating to the city of Hwaseong.
- The Ulsan 'Hydrogen Town' project, which aims to create the world's first hydrogen community, using hydrogen to power transport, homes, public buildings and businesses.[139]
- Subsidies that halve the cost of businesses and residences installing hydrogen fuel cells, under the '1 Million Green Homes Programme'.

133 ENE-FARM fuel cells extract hydrogen from the natural gas network but are designed to eventually run on 100% hydrogen.
134 Lefteris Karagiannopoulos et al, "Norway races Australia to fulfill Japan's hydrogen society dream", Reuters, 28 April 2017, accessed July 11, 2018, https://www.reuters.com/article/us-japan-hydrogen-race-idUSKBN17U1QA
135 Stephen Crolius, "Japan, Saudi Arabia explore trade in hydrogen, ammonia", *Ammonia Energy*, 15 February 2018, accessed July 11, 2018, http://www.ammoniaenergy.org/japan-saudi-arabia-explore-trade-in-hydrogen-ammonia/
136 Co-funded by METI, the Tokyo Metropolitan Government and the stations' operator.
137 Jim Motavalli, "South Korea's ambitious plans for hydrogen-power plants and cars", *FuelCellCars.com*, 24 June 2016, accessed July 11, 2018, http://www.fuelcellcars.com/south-koreas-ambitious-plans-for-hydrogen-power-plants-and-cars/
138 Paul Dvorak, "Korea sets a goal of 310 refuelling stations by 2022", *Windpower Engineering & Development*, 7 February 2018, accessed July 11, 2018, https://www.windpowerengineering.com/electrical/electric-vehicles/310-hydrogen-refuelling-stations-korea-2022/
139 Hang-soo Wang, "Hydrogen Energy toward high value-added industry for Ulsan", Green Energy Conference, Ulsan, 28-30 June 2016, accessed July 11, 2018, https://isid.unido.org/files/Gic2016/conference_proceedings/WooHang-soo_presentation_Plenary%201_GIC%202016.pdf

5.4.3 Europe

- The Fuel Cells and Hydrogen Joint Undertaking, a partnership between the European Commission, industry and research groups, is investing €1.33 billion in hydrogen research, development and demonstration projects.
- In Germany, the Energiepark Mainz project has a 6 MW electrolysis hydrogen production unit. The electrolyser is connected to the local electricity network and produces hydrogen for injection into the local gas grid as well as a multi-use filling station.
- Also in Germany, Alstom and the local transport authority of Lower Saxony (LNVG) have signed a contract for the delivery of 14 hydrogen fuel cell trains. Alstom's Coradia iLint Hydrogen train was recently approved for passenger service run.
- In France, the Ministry of Environment has announced €100 million for hydrogen development in mobility, energy and industry.
  - French energy company Engie is building a large hydrogen refuelling station in the Rungis market district of Paris. It will have the capacity to power a hydrogen utility fleet consisting of 50 Renault vans.
  - Engie's GRHYD project in Dunkirk, meanwhile, is trialling a refuelling station for buses and the injection of up to 20% hydrogen into the local gas network, supplying 200 homes.[140]
- In the United Kingdom, the government's Clean Growth Strategy has identified 100% conversion of the gas distribution network to hydrogen as one of the most credible large-scale decarbonisation options.[141]
  - The H21 Leeds City Gate feasibility study investigated the technical and economic feasibility of converting the Leeds gas supply to hydrogen. The city has a population of about 800,000.
  - The government has committed £25 million and the gas industry £10 million to provide safety evidence for hydrogen use in buildings and pipelines and to stimulate the development of appliances in support of the conversion strategy.
  - A conceptual design for converting the north of England to hydrogen between 2028 and 2035 is expected to be released by the end of 2018.
  - London is part of the 'Clean Hydrogen in European Cities' trial, with eight fuel cell buses in use in Central London since 2011.[142]

140 "The GRHYD demonstration project", Engie, accessed July 11, 2018, https://www.engie.com/en/innovation-energy-transition/digital-control-energy-efficiency/power-to-gas/the-grhyd-demonstration-project/
141 British Government, *The Clean Growth Strategy: Leading the way to a low carbon future*, October 2017, accessed July 11, 2018, https://www.gov.uk/government/publications/clean-growth-strategy
142 "London", Clean Hydrogen in European Cities, accessed July 11, 2018, http://chic-project.eu/demonstration-sites/london

5.4.4 China

- The Chinese Ministry of Science & Technology (MOST) has supported fuel cell vehicle initiatives since 2000 under an environmental project of the United Nations Development Programme. The project has led to a total of 109 fuel cell buses being deployed in several cities.[143]
- Wuhan, the capital city of Hubei province, plans to become a 'hydrogen city' through developing a hydrogen energy industry.[144]
- Hebei province set up a project in 2014 using surplus energy from a 200 MW wind farm to make hydrogen for use in fuel cell vehicles.
- Sifang, a subsidiary of China South Rail Corporation, has developed the world's first hydrogen-powered tram, now running in the city of Tangshan, Hebei province.[145]
- Jilin province has conducted a trial of hydrogen blended with natural gas for use in internal-combustion vehicles.
- Battery maker Shenzhen Center Power Tech intends to invest up to CNY500 million (about US$75 million) in developing hydrogen fuel cells.[146]

5.4.5 United States

- Nikola Motors, founded in 2014, has developed a hydrogen-powered Class 8 truck (the format commonly referred to as a semi-trailer in Australia) that can pull a load of 36 tonnes. Depending on load, the range is up to 1,900 km.[147] The drivetrain is a series hybrid configuration in which a fuel cell constantly charges a battery that supplies the electricity to the motors, the same configuration used in diesel electric locomotives. In May 2018, brewing company Anheuser-Busch ordered up to 800 Nikola One trucks for delivery commencing 2020.[148]

143 "China homes in on hydrogen", Medium, accessed July 23, 2018, https://medium.com/@cH2ange/china-homes-in-on-hydrogen-977b37ddcca9
144 *Xinhua*, "Hydrogen city to be built in central China", 21 January 2018, accessed July 23, 2018, http://www.xinhuanet.com/english/2018-01/21/c_136913339.htm
145 *Xinhua*, "World's first hydrogen tram runs in China", 27 October 2017, accessed July 23, 2018, http://www.xinhuanet.com/english/2017-10/27/c_136709647.htm
146 "Shenzhen Center Power plans to invest USD75 million to develop hydrogen fuel cells", Yicai Global, accessed July 23, 2018, https://www.yicaiglobal.com/news/shenzhen-center-power-plans-invest-usd75-million-develop-hydrogen-fuel-cells
147 "Nikola One", Nikola Motors, accessed July 12, 2018, https://nikolamotor.com/one#motor-specs-bottom
148 Jennifer Smith, "Anheuser-Busch will buy Nikola's hydrogen-powered trucks", The Wall Street Journal, 3 May 2018, accessed July 19, 2018, https://www.wsj.com/articles/anheuser-busch-will-buy-nikolas-hydrogen-powered-trucks-1525352410

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