ENERGY AND FUTURES
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# National Hydrogen Roadmap

Pathways to an economically sustainable hydrogen industry in Australia

## EXECUTIVE SUMMARY


NWP : 70MPa
H2
GAS
H2
Hydrogen
CAUTION

# Executive summary

## Introduction

### WHY HYDROGEN?

Clean hydrogen is a versatile energy carrier and feedstock that can enable deep decarbonisation across the energy and industrial sectors.

Hydrogen gas ('hydrogen') is a versatile energy carrier and feedstock, derived primarily by splitting water or by reacting fossil fuels with steam or controlled amounts of oxygen. While hydrogen has served mostly as an input into a range of industrial processes, it has the potential to be used across a number of applications as shown below. Further, if produced using low or zero emissions sources, ('clean') hydrogen can enable deep decarbonisation across the energy and industrial sectors. Clean hydrogen is the focus of this report.

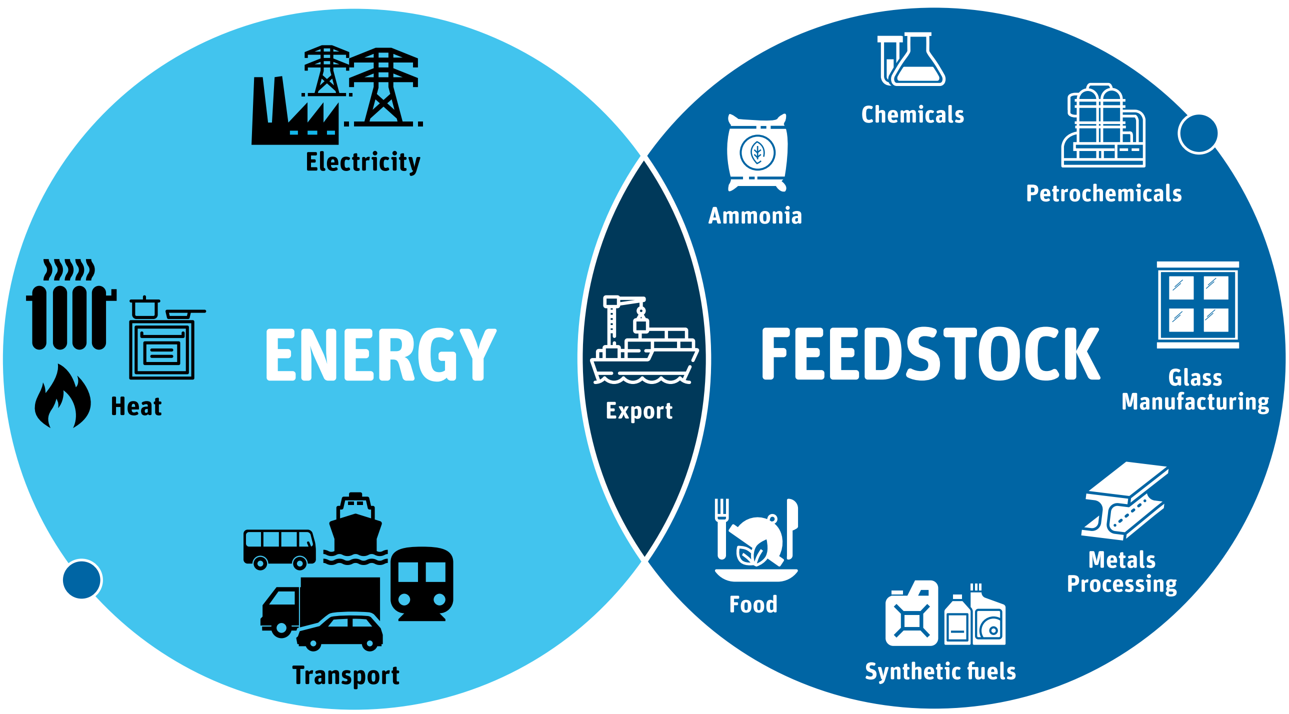
### WHY AUSTRALIA?

Australia has the resources and skills to build an economically sustainable domestic and export hydrogen industry which can help meet agreed emissions targets and address concerns around energy security.

In 2016, Australia ratified the Paris Agreement, committing to achieve a 26-28% reduction in greenhouse gas emissions below 2005 levels by 2030. While use of hydrogen across the energy and industrial sectors is one of a suite of technology options that can play a role in helping Australia meet the prescribed decarbonisation targets, there are a number of other domestic trends and characteristics that favour its widespread use. These include:

- **Natural gas supply**: Particularly on the east coast of Australia, gas prices currently remain high (\$8-10/GJ) compared to some overseas markets, with some uncertainty regarding future cost trajectories. Hydrogen could replace natural gas as a low emissions source of heat as well as a potentially cost competitive low emissions feedstock for a number of industrial processes.

### APPLICATIONS FOR HYDROGEN



- **Changing electricity sector**: Hydrogen can help manage the transition to a higher proportion of variable renewable electricity (VRE) in the electricity network by overcoming challenges associated with energy intermittency. Hydrogen also offers an opportunity for optimisation of renewable energy use between the electricity, gas and transport sectors (i.e. 'sector coupling').
- **Liquid fuels security**: Australia has long been dependent on imported liquid fuels and at present, is not meeting domestic fuel reserve targets. Hydrogen can play a key role in protecting Australia from supply shocks by localising liquid fuel supplies (e.g. by producing synthetic fuels) or by displacing their use in both stationary and transport applications.
- **Skilled workforce**: Australia has a technically skilled workforce with deep expertise across the energy sector as well as in high value or advanced manufacturing production processes. There is a strong need for these skills across the hydrogen value chain and so this represents an opportunity to transition the workforce to a growth market.

In relation to export markets, Australia has a rich history of generating economic opportunities through export of its natural resources. Some of these markets, for example uranium, have suffered downturns as a consequence of a changing energy mix abroad. Others such as thermal coal, could be at risk in the future if global trends continue to lead towards a low carbon economy.

In contrast, the global market for hydrogen is expected to reach USD155 billion by 2022[1], with a number of Australia's existing trading partners such as Japan, who are comparatively resource constrained, currently implementing policy commitments for hydrogen imports and use. **Australia's extensive natural resources, namely solar, wind, fossil fuels and available land lend favourably to the establishment of hydrogen export supply chains.**

### WHY NOW?

Globally, the hydrogen industry is underpinned by a series of mature technologies and relevant markets are on the verge of reaching a 'tipping point'.

While interest levels in the development of global hydrogen industries have fluctuated over recent decades, today there are a number of trends and activities that distinguish the renewed focus on hydrogen from what has been observed previously. This includes policy commitments from countries across Europe and Asia as well as increasing investment from multinational technology manufacturers and energy companies.

The primary difference however is that the hydrogen value chain is now underpinned by a series of mature technologies that are being demonstrated in pilot projects globally. Although there is considerable scope for further R&D, **this level of maturity has meant that the narrative has shifted from one of technology development to market activation**. This involves the transition from emerging technologies to bankable assets, similar to what has recently been observed in the solar PV industry.

## This report

Recently there has been a considerable amount of work undertaken (both globally and domestically) that seeks to quantify the economic opportunities associated with hyrdogen. This report takes that analysis a step further by focussing on how those opportunities can be realised.

**The primary objective of this report is to provide a blueprint for the development of a hydrogen industry in Australia (i.e. market activation). With a number of activities already underway, it is designed to help inform the next series of investment amongst various stakeholder groups (e.g. industry, government and research) so that the industry can continue to scale in a coordinated manner.**

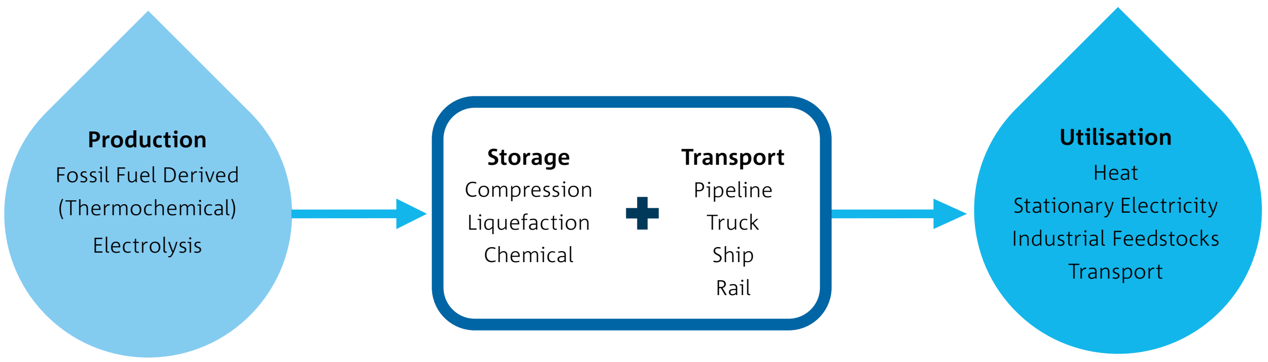
## Development of a hydrogen industry

Barriers to market activation stem from a lack of supporting infrastructure and/or the cost of hydrogen supply. However, both barriers can be overcome via a series of strategic investments along the value chain from both the private and public sector.

1 International Energy Agency Hydrogen Technology Collaboration Program 2017, Global Trends and Outlook for Hydrogen

A snapshot of the underpinning hydrogen value chain is set out below.

### Hydrogen value chain

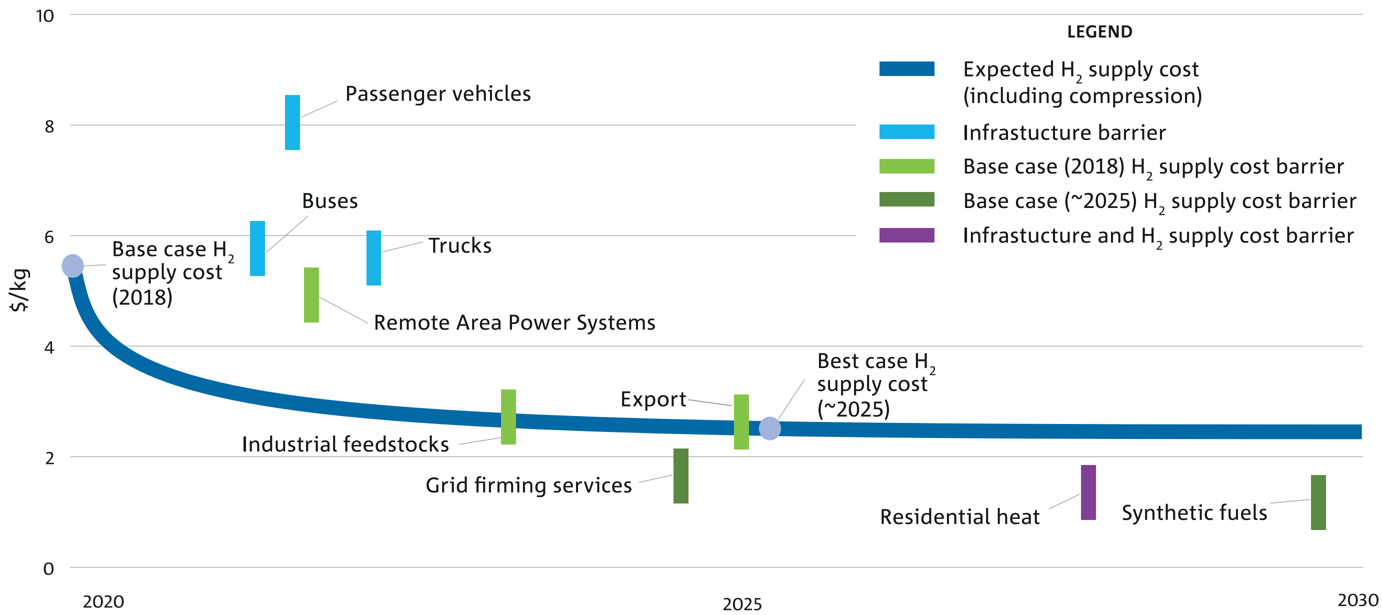



Barriers to market activation stem from a lack of infrastructure required to support each application and/or the cost of hydrogen supply when compared to other energy carriers (e.g. batteries) and feedstocks (e.g. natural gas). **It is expected however, that development of an appropriate policy framework could create a 'market pull' for hydrogen. Investment in infrastructure, hydrogen production, storage and transport is then likely to follow.**

Implementation of the key investment priorities identified through the report could see the hydrogen industry scale in a manner depicted in the figure below. This demonstrates the expected reductions in the cost of hydrogen supply and the progression of target markets based on when hydrogen could be **commercially competitive** with alternative technologies. It also identifies where the barrier to market is infrastructure (i.e. above the hydrogen cost curve) and/or the cost of hydrogen supply (i.e. below the hydrogen cost curve).

The competitiveness of hydrogen against other technologies is likely to then improve when considering factors such as localisation and automation of supply chains, energy supply and carbon risk as well as the establishment of a hydrogen export industry. Further, while each application has been assessed individually, a unique advantage of hydrogen is that it can simultaneously service multiple sources of demand. Thus in practice, a single hydrogen production plant could secure offtake agreements in a number of applications depending on available infrastructure, policy and demand profiles.

### Hydrogen competitiveness in targeted applications



The following sections illustrate how each element of the hydrogen value chain can develop according to the above figure. Key investment priorities across the value chain are subsequently outlined in the 'summary of priorities' table.

## Hydrogen production

**Hydrogen may be produced via two mature pathways:**

- **Thermochemical**: Uses a fossil fuel feedstock to produce hydrogen. This process must be paired with carbon capture and storage (CCS) to produce clean hydrogen. Mature technologies include steam methane reforming (SMR) which relies on natural gas as an input, and coal gasification
- **Electrochemical**: Involves the use of an electrical current to split water into hydrogen and oxygen. Requires the use of low or zero emissions electricity to produce clean hydrogen. Mature technologies include polymer electrolyte membrane (PEM) and alkaline electrolysis (AE)

### THERMOCHEMICAL

Thermochemical hydrogen production must be built at scale (i.e. > 500,000kg/day) to offset the capital cost of the generation plant and accompanying $CO_2$ storage reservoir. While the industry is in a development phase, projects of this scale would very quickly saturate a domestic market and so rely on the development of a hydrogen export industry in order to secure the requisite offtake agreements.

Although SMR is currently the cheapest form of hydrogen generation, investment in new large scale demand may prove challenging given the current state of the natural gas industry in Australia (as discussed previously). Further, black coal gasification has challenges in an Australian context due to coal reserves being concentrated in NSW and Queensland where there are either no well-characterised, or only onshore $CO_2$ storage reservoirs that carry a higher social licence risk.

Hydrogen production via brown coal in Victoria's Latrobe Valley therefore represents the most likely thermochemical hydrogen production project. A prospective plant would have the advantage of an extensive brown coal reserve sitting alongside a well characterised $CO_2$ storage reservoir in the Gippsland Basin. This project is most likely to be commercialised via the proposed Hydrogen Energy Supply Chain (HESC).

Pending successful demonstration in 2020/2021 and subsequent improvements in efficiencies, hydrogen could be produced in the region for approximately $2.14 -2.74/kg[2] once the commercial scale production and CCS plant come online in the 2030s.

### ELECTROCHEMICAL

Electrolysis provides a more modular, distributed option that can scale according to demand. It is therefore more likely to meet the majority of hydrogen demand prior to 2030 and the expected cost curve is reflected in the hydrogen competitiveness figure.

AE is currently the more established and cheaper technology (~$5.50/kg) and will therefore continue to play an important role in the development of the industry. Despite its level of maturity, incremental improvements in AE can still be achieved through subtle gains in efficiency.

Although currently more expensive, PEM electrolysis is fast becoming a more competitive form of hydrogen production. It also offers a number of other advantages over AE including faster response times (which makes it more suitable for coupling with VRE) and a smaller footprint for scenarios in which there are limitations on space (e.g. hydrogen refuelling stations). RD&D is expected to lead to improvements in PEM plant design and efficiencies. Increases in production economies of scale are also likely to reduce technology capital costs.

The cost of hydrogen from both types of electrolysis can be significantly reduced via the scaling of plant capacities (e.g. from 1MW to 100MW), greater utilisation and favourable contracts for low emissions electricity (e.g. 4c/kWh). With a number of demonstration projects likely over the next three to four years needed to de-risk these assets at scale, it is expected that costs could reach approximately $2.29-2.79/kg by 2025.

2 This modelling was undertaken by CSIRO and only contains information that has been made publically available by members of the HESC project

## Storage and transport of hydrogen

**Hydrogen storage technologies can be broadly classified as:**

1. **Compression**: Gaseous hydrogen stored at higher pressures to increase volume. Includes large scale underground storage (e.g. salt caverns) and 'line packing' in gas pipelines
2. **Liquefaction**: Pressurising and cooling hydrogen to -253˚C so that it is in a liquid state
3. **Chemical**: Molecules such as ammonia, metal hydrides and toluene that carry hydrogen. All retain an additional energy penalty and cost associated with the recovery of hydrogen prior to use

### STORAGE OF HYDROGEN

Storage of hydrogen represents a key component in hydrogen supply. Due to the low volumetric density of hydrogen in its gaseous state, a series of technologies may be utilised in order to improve the economics of storage (i.e. higher volumetric densities allow for greater quantities of hydrogen to be stored inside a tank of fixed size). Selection of the most appropriate storage technology represents a trade-off between the quantity of hydrogen, storage footprint (e.g. tank size) and energy usage.

Compression of gaseous hydrogen generally represents the most attractive option for stationary storage given the comparatively lower cost and greater availability of space. With likely improvements in compression efficiencies, storage of hydrogen is expected to add ~$0.3/kg to the cost of hydrogen produced by 2025 (as reflected in the hydrogen competitiveness figure).

Other storage technologies including liquefaction and material carriers such as ammonia have a superior volumetric density but higher cost. These technologies therefore become more financially viable when storing (or transporting) larger quantities of hydrogen where there are stringent space limitations in place. With expected improvements, liquefaction is likely to add an additional $1.59-1.94/kg to the cost of hydrogen produced by 2025.

As an alternative, ammonia synthesis (via the traditional Haber-Bosch process) could add an additional $1.10-1.33/kg to the cost of hydrogen, albeit with ammonia as the product[3]. A direct comparison with liquefaction cannot be made at this stage given that there is an additional energy and capital cost associated with recovery of high purity hydrogen from the ammonia at the point of use. Relevant hydrogen separation technologies currently being developed represent a key piece in the supply chain but are not yet mature enough to gain a meaningful assessment of cost.

### TRANSPORT OF HYDROGEN

Hydrogen can be transported via truck, rail, ship and pipeline utilising the storage techniques identified. Although not reflected in the hydrogen competitiveness figure due to variability, greater distances between the point of generation and use increases supply chain costs.

Coupling of storage and transport technologies typically requires consideration of a number of factors including hydrogen demand, available infrastructure and distance. While compression has been commonly used for trucks, liquefaction is now also increasingly utilised where distances approach 1000km.

For domestic use, pipelines are also important for transport of larger quantities of compressed gaseous hydrogen over long distances (i.e. transmission) as well as distribution to multiple points of use in a network (i.e. distribution).

As round trip distances (i.e. >4000km) and demand for hydrogen increase, technologies with greater hydrogen densities such as ammonia synthesis and liquefaction are likely to be preferred. These technologies are being developed further given their potential role in export of hydrogen via ship.

3 This refers to the cost of the hydrogen carried within the ammonia product rather than simply the cost of ammonia

## Applications for hydrogen (utilisation)

### HYDROGEN FUELLED TRANSPORT

Hydrogen fuelled transport represents an early target market in the development of a hydrogen industry. This is particularly true if there is a zero emissions or air quality target for the sector, given the applicability of hydrogen to all forms of transport.

In the passenger vehicle market, fuel cell electric vehicles (FCEV) represent a potentially more favourable option (compared with battery electric vehicles (BEVs)) for consumers that travel longer distances (i.e. 400-600km without refuelling) and expect shorter refuelling times. For heavier vehicles such as buses and trucks with stringent payloads, the relative weight of hydrogen (compared with batteries) also allows for greater distances travelled without the need for refuelling. The primary barriers to market however are the current capital cost of FCEVs and lack of infrastructure supporting their use.

While R&D into the improvement of FCEVs is ongoing, the most material reductions in capital costs will stem from economies of scale in manufacture and through dedicated and automated production lines. For the passenger vehicle market in particular, given that Australia currently comprises approximately 2% of the global market, it is expected that increases in scale will be dictated by consumer trends overseas. Globally, leading car manufacturers expect to reach requisite targets, allowing for mass market vehicle production by 2025. However, vehicle uptake will still need to be stimulated in Australia through the implementation of vehicle emissions standards and/or specific incentives.

The success of the FCEV market in Australia rests largely on the strategic deployment of hydrogen refuelling stations. Depending on the configuration, current costs range from USD1.5 to USD2.0 million per station. With an extensive deployment of refuelling stations ongoing in jurisdictions such as Germany, it is likely that there will be a shift away from ad hoc demonstrations to standard roll out of reliable equipment. This is expected to lead to a significant reduction in capital (i.e. USD0.5 to USD1.0 million) and operating costs by 2025.

Deployment of refuelling stations require a high degree of coordination between station operators and car manufacturers (i.e. to match hydrogen supply and demand). This has been achieved overseas through the use of joint ventures that are responsible for the roll out of a high volume of stations in a specified region (e.g. 100 stations in a 3-5 year period). Within these arrangements, there is also a key role for Government in underwriting initial demand risk and facilitating the development of relevant operating standards.

Australia has the benefit of rolling out station models that have already been developed overseas. If a series of demonstration projects were to be implemented in the next 5 years, these stations could be commonplace by 2025.

### REMOTE AREA POWER SYSTEMS (RAPS)

Diesel based RAPS currently have a high cost due to the need to import fuel via truck to remote communities. These systems also have an adverse environmental impact.

With expected reductions in the cost of hydrogen and fuel cells (needed to generate electricity), hydrogen based RAPS (using dedicated renewable energy inputs) could be commercially competitive with diesel equivalents before 2025. Key targets for demonstration over the next three to four years should include smaller remote mining operations due to the ability for hydrogen to service multiple operations on a single site (e.g. materials handling, transport, heat and wastewater management).

### INDUSTRIAL FEEDSTOCKS

Use of clean hydrogen as an industrial feedstock involves direct displacement of hydrogen derived from SMR as the incumbent source of production. The breakeven point will be driven by the price of natural gas against reductions in the cost of hydrogen via electrolysis. This is expected to occur before 2025. Thus there is less that must be done in terms of market activation other than incentivise use of clean hydrogen in these processes before it is commercially competitive.

Use of hydrogen in the petrochemical industry, as a means of treating and refining crude oil has been declining due to Australia's growing dependence on imported refined fuel products. However with increasing concern over the need to reduce Australia's dependence on liquid fuel imports and decarbonise the transport sector, there could be a role for hydrogen in treating fuels derived from biomass.

Input of clean hydrogen into ammonia and other chemicals such as methanol could renew demand for these products as the world transitions to a low carbon economy.

## EXPORT

Export of hydrogen represents a key opportunity for Australia. Potential demand for imported hydrogen in China, Japan, South Korea and Singapore could reach in the order of 3.8 million tonnes in 2030[4] (~AUD9.5 billion) with Australia well positioned to play a key role in the export market.

Development of this industry is largely dependent on the production, storage and transport technologies identified above with many lessons to be gained from the export of LNG. Given that commercial scale production of hydrogen from brown coal in Victoria is only likely to be available after 2030, the majority of prior demand is expected to be met by electrolysis coupled with dedicated renewables and/or grid connected electricity. A target hydrogen production price of $2-3/kg (excluding storage and transport) is likely to be needed for Australia to compete with other exporting countries.

## ELECTRICITY GRID FIRMING

Hydrogen systems can provide both electricity grid stability (i.e. seconds to hourly storage) and grid reliability (i.e. seasonal storage) services. There is likely to be an increasing demand for these services as the proportion of VRE in the network continues to increase over the next five years.

In the first instance, grid connected electrolysers provide a flexible load that can be ramped up and down to help manage grid stability. On the other hand, hydrogen systems consisting of storage and fuel cells are unlikely to be constructed for the sole purpose of grid stability, due to the need for a hydrogen price of less than $2/kg to compete with batteries, pumped hydro and gas turbines.

However, for grid reliability, hydrogen systems (along with gas turbines) present one of the only technological solutions to overcoming challenges with seasonal intermittency. While gas turbines are likely to be cheaper, the price differential could be minimised when considering carbon and natural gas supply risks associated with building new natural gas assets.

## HEAT

Direct combustion of hydrogen for the purpose of generating heat is unlikely to compete with natural gas on a commercial basis before 2030. This form of utilisation would therefore need a clear policy signal from government focussed on decarbonisation of the gas networks in order for this conversion to occur.

Hydrogen enrichment of the natural gas network provides an early market for hydrogen and a shorter term option for decarbonisation of the sector without the requirement for a significant upgrade of existing infrastructure. However, due to different burner properties and characteristics of the gases, a move to 100% displacement of natural gas with hydrogen will require an upgrade to existing appliances and possibly pipelines.

Industrial appliances such as furnaces and kilns are complicated due to integration with other systems on a single site. Upgrading from natural gas to hydrogen in this sector is therefore likely to be more ad hoc.

In contrast, upgrading residential appliances is technically more straightforward and a widespread roll out could be possible in or around 2030. The challenge is coordinating the appliance change with the switchover in gas supply. This has been demonstrated in Australia with prior conversions from town gas (consisting of ~50% hydrogen) to natural gas in the 1970s.

Where possible, this risk can be somewhat mitigated by the placement of electrolysers at the pipeline distribution network and by mandating the manufacture and installation of standardised and more easily convertible appliances before the switchover occurs.

## SYNTHETIC FUELS

Synthetic fuels are unlikely to compete with crude derived fuels on a purely commercial basis. However as discussed in the context of biofuels, this could change if there is an identified need for a localised fuel supply.

This may be achieved through the production of syngas as an intermediary via coal gasification and/or SMR, which can then be used to produce higher order synthetic fuels. However, this process still has a significant emissions profile. As an alternative, ‘power-to-liquids’, which combines hydrogen with a waste stream of $CO_2$, could be used to synthesise lower emissions fuels that are likely to play an important role in heavier forms of transport such as aviation and shipping.

4 ACIL Allen Consulting, 2018, Opportunities for Australia from hydrogen exports, Australia (ARENA Report)

**SUMMARY OF PRIORITIES**

| VALUE CHAIN ELEMENT | COMMERCIAL | POLICY/REGULATORY | RD&D | SOCIAL |
|---|---|---|---|---|
| General | • Implement vertical integration along the supply chain to optimise technology selection and use<br>• Implement joint ventures to allow for allocation of risk and coordination of resources<br>• Provide access to lower cost financing for low emissions projects | • Implement targeted policies to stimulate hydrogen demand<br>• Develop hydrogen specific regulations based on best practice global standards. These should be uniform across the States and Territories<br>• Establish inter/ intragovernmental hydrogen authorities | • Continue demonstration projects for mature technologies to overcome 'first of kind' risk<br>• Establish centralised RD&D bodies consisting of researchers, industry and government to coordinate RD&D funding appropriately (e.g. 'Hydrogen Centre of Excellence')<br>• Implement incentives for local manufacturing | • Develop engagement plans and undertake demonstration projects to showcase hydrogen and ensure communities understand all aspects of its use |
| Supply | | | | |
| Production | • Position production plant to accept multiple offtakes for hydrogen<br>• Secure cheap low emissions electricity | • Develop 'Guarantees of Origin' scheme<br>• Government to secure long-term storage liability for $CO_2$ storage<br>• Allow for compensation for grid firming services from electrolysers | • Continue RD&D into improving plant efficiencies and asset life<br>• Continue development of less mature technologies such as high temperature electrolysis and methane cracking | • Undertake stakeholder engagement on technical viability and safety of CCS |
| Storage and Transport of $H_2$ | • Position plants close to point of hydrogen use where possible | • Review gas pipeline regulations to consider including gaseous hydrogen | • Develop capabilities in liquefaction materials<br>• Continue R&D in 100% hydrogen capable pipeline materials and pressures<br>• Develop higher efficiency compression technologies and underground storage | • Develop communication plans regarding hydrogen pipeline easements |

| VALUE CHAIN ELEMENT | COMMERCIAL | POLICY/REGULATORY | RD&D | SOCIAL |
|---|---|---|---|---|
| **Applications** | | | | |
| Hydrogen fuelled transport | • Establish refuelling station joint ventures and undertake strategic roll out of stations | • Implement emissions standards on vehicles and specific incentives for FCEVs | • Demonstrate viability of refuelling stations with 'back to base' vehicles or vehicles with known driving patterns | • Improve recognition of FCEVs as electric vehicles<br>• Conduct ongoing station safety demonstrations for refuelling stations |
| Industrial feedstocks | • Install new clean hydrogen inlets into facilities during plant shutdowns | • Implement incentive schemes regarding use of clean hydrogen as an industrial feedstock | | • Create awareness of emissions embodied in commodities to help inform consumer choice |
| Export (as per production, storage and transport plus) | • Implement government to government agreements for export to give industry confidence<br>• Establish 'take or pay' export offtakes<br>• Undertake land appraisal assessments for dedicated renewables<br>• Invest in domestic labour force<br>• Negotiate favourable tariffs for hydrogen export (including in the existing FTAs) | • Implement regulations supporting use of unutilised land for dedicated renewables<br>• Engage bodies such as the International Maritime Organisation to ensure appropriate regulatory frameworks for hydrogen shipping | • As per hydrogen production, storage and transport | • Continue to promote hydrogen as a low emissions export commodity |
| Electricity grid firming and RAPS | • Undertake remote communities appraisal for RAPS | • Implement incentives for use of hydrogen in remote mining sites and communities | • Continue RD&D into fuel cells to improve capital costs and asset life<br>• Demonstrate hydrogen in RAPS in mining activities and remote communities | • Develop engagement plans regarding use of hydrogen systems in remote communities |
| Heat | • Invest in 100% hydrogen capable workforce and appliance fitters<br>• Coordinate with non-Australian governments to give multinational appliance manufacturers more certainty | • Implement clear policy direction for enrichment and subsequent displacement of natural gas<br>• Legislate manufacture and use of standardised and easily convertible appliances | • Continue R&D in 100% hydrogen appliances<br>• Continue trials for natural gas enrichment with hydrogen<br>• Undertake feasibility study over designated town for 100% hydrogen<br>• Begin development of pilot project for designated town | • Undertake hydrogen enriched natural gas demonstrations to familiarise consumers with burning hydrogen |
| Synthetic fuels | | • Mandate local and low emissions fuel supply targets<br>• Implement incentives for use of synthetic fuels in aviation and shipping industry | • Invest in 'power-to-fuels' technologies | |

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