THE MCKELL INSTITUTE

First Mover Moment

Making the Most of Australia's Hydrogen Opportunity

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About this Report

This project has been prepared by the McKell Institute for the Australian Workers' Union.

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Foreword

Australia is in the midst of a remarkable energy transition. With the election of the Albanese Government in 2022, Australia is now committed to a 43 per cent emissions reductions pledge, on 2005 levels, by 2030 and is targeting net-zero emissions by 2050.

Such a transformation creates profound opportunities for Australia – a country that has always enjoyed advantages when it comes to energy production.

For decades, Australia's coal and natural gas industries have given the country an edge. These energy sources have fuelled local industry, and served as valuable exports to the rest of the world. But it is clear that the insatiable demand for these fossil fuels will decrease over time as the world seeks new, cleaner forms of energy to power their economies.

Despite the challenges associated with this transition, Australia is uniquely positioned to emerge as an energy superpower in this new paradigm.

One of the most lucrative opportunities for Australia in a world on the path to net zero will be the export of hydrogen. Hydrogen can be used as an industrial energy source or feedstock, much like oil or gas, but the burning of hydrogen itself results in no greenhouse gas emissions. This provides a clean alternative for industrial manufacturers that currently rely on emissions-intensive coal or natural gas in manufacturing processes. As well as enabling an export boom, the availability of cheap domestically made hydrogen would give Australian manufacturers a competitive edge in producing green industrial goods.

Producing hydrogen, however, is itself energy intensive. And while great strides have been made in advancing green hydrogen production — the production of hydrogen using emissions-free energy — it is likely that green hydrogen will not be produced at scale in Australia well into the 2030s. Currently, commercial-scale hydrogen production utilises fossil fuels, which would require carbon capture technologies in order to reduce emissions.

This creates a conundrum for Australian policymakers: while Australia is well positioned to emerge as a green hydrogen export leader in the 2030s, there are still short-term steps that need to be taken. Global demand for hydrogen will increase in the next decade, but for Australia to capitalise on this, the domestic hydrogen industry needs to see rapid development of its own.

This report explores this challenge, and advances three key recommendations that can be adopted in order to set up Australia as a hydrogen export leader in the coming decades.

Executive Summary

This report begins by outlining the hydrogen opportunity in Australia and the world. As addressing climate change becomes a more urgent global priority, governments around the world have begun pursuing alternative energy policies in order to meet their Nationally Determined Contributions (NDCs) – the emissions reductions that countries have committed to undertake under the *United Nations Framework Convention on Climate Change.*

A significant proportion of greenhouse gas emissions can be abated with electrification powered by solar, wind, storage, hydro, and other clean sources such as geothermal, however some carbon-intensive industries and practices will require an alternative fuel. For example, providing energy at the massive scale needed for Australia's heavy industry – like making steel, concrete, cement, and aluminium – remains challenging.

For this reason, hydrogen presents an exciting opportunity. Although energy intensive to produce, hydrogen is emissions-free when burned, and if clean energy production methods are utilised, hydrogen can be a low or zero-emissions fuel. With a vast natural endowment of clean energy possibilities, and an economy built around natural resource exports, Australia is ideally positioned to capitalise on this opportunity.

Part 2 of this report then examines the current and future global market for hydrogen, noting the myriad applications of hydrogen that will drive demand as the world transitions towards net zero. Although it is expected that demand for hydrogen will increase massively during the 2030s, it is already in wide use today, and this existing demand can be leveraged and expanded upon to help Australia's domestic industry scale up this decade.

Part 3 then outlines the first mover advantage Australia should chase today so that the forecast green hydrogen export opportunities can be met in coming decades. It is essential Australia implements its plans for a future green hydrogen export economy. This ideal outcome can be made more certain by facilitating the timely development of the associated infrastructure, networks and customer bases required for this export economy. By developing scale, maximising hydrogen production, and ultimately driving down costs this decade, Australia can meet the moment and become a first mover in global markets for hydrogen, and the range of green manufactured goods it can produce.

Part 4 details the various approaches that Australian governments have taken to date on the hydrogen opportunity. Over the past decade, all Australian governments have begun to recognise the immense opportunities that hydrogen production and exports will bring. Some governments have already invested in capital works have already been invested in by some governments in order to bring production online in coming years.

Finally, the report makes three key recommendations aimed at guiding national hydrogen policy in the coming decade. It argues that governments should prioritise scale, work with industry to identify the most appropriate way in which domestic hydrogen production to help grow domestic manufacturing, and design a national Hydrogen Domestic Reservation Mechanism today, to avoid future supply shortfalls when hydrogen is an essential input for Australian heavy industry.

Key Findings

1. Australia is well positioned to become a major player in the global hydrogen market if it takes advantage of all-available hydrogen production opportunities in the short, medium, and long-term.

2. Though the global market for hydrogen is forecast to expand greatly in the next decade, there is already existing demand for hydrogen that Australia is well positioned to leverage in the near-term.

3. Achieving scale in hydrogen production will be key to enabling an Australian hydrogen export economy to materialise. A near-term policy priority for the Commonwealth and state governments should be maximising clean hydrogen production scale, irrespective of whether it is production of blue or green hydrogen.

4. Even as Australia pursues its medium-term emissions target of a 43 per cent reduction, existing industrial fossil fuel users will continue to require clean and efficient heat, as well as chemical feedstocks. In the 2030s, Australian-produced green hydrogen is expected to meet this demand. In the interim, however, blue hydrogen with effective carbon capture and storage can offer a less emissions-intensive alternative to natural gas and coal.

5. To realise Australia's vision to become a renewable energy superpower, jobs will be created in manufacturing utilising renewable energy. Scaling up clean hydrogen production and developing renewables means a considerable amount of new equipment and infrastructure will be necessary. This presents an opportunity to stimulate blue-collar employment by manufacturing these capital goods domestically.

6. To be considered 'blue' and not 'grey', hydrogen producers rely on carbon capture and storage (CCS) solutions to minimise carbon emissions associated with the production of non-green hydrogen. To date, CCS in Australia has had a patchy record. This alone should not preclude the development of blue hydrogen projects, so long as CCS is unequivocally demonstrated to be effective prior to project approval.

7. While Australia is well positioned to capture a portion of the medium-term hydrogen export market, there are numerous infrastructure deficits that currently stand in the way of Australian exports of hydrogen, irrespective of its type. Ports and shipping solutions, in particular, are in need of considerable development, and require the scaled production of hydrogen to become economically feasible. While governments should work to address this infrastructure and scale deficit in a coordinated fashion, and to do so this decade, developing a domestic market for hydrogen should also be an immediate priority.

Summary of Recommendations

Recommendation 1: The Australian Government should prioritise the expeditious scaling of hydrogen production this decade, irrespective of type, in order to maximise the opportunity for a clean hydrogen export economy to succeed in the 2030s and beyond.

For Australia to develop the supportive infrastructure, skilled workforce, transportation systems and customer relationships to enable green hydrogen exports in the future, governments need to prioritise the scaling of the hydrogen industry this decade.

Recommendation 2: The Australian Government should explore ways to accelerate the use of hydrogen in existing industrial processes to support domestic renewable energy manufacturing.

Utilising cheap and abundant hydrogen can give Australia a competitive advantage when it comes to manufacturing, including the manufacturing of clean-energy products.

Recommendation 3: Develop a Hydrogen Reservation Mechanism, safeguarding future industrial uses of hydrogen from domestic shortfalls during global energy shocks.

To ensure Australian industry is not adversely impacted by domestic hydrogen supply shortfalls in the future, as has been seen in 2022 with gas shortfalls, the Australian Government should consider designing and legislating a national Hydrogen Reservation Mechanism during this term of parliament.

Glossary of Terms

TERM	ACRONYM	DEFINITION
Hydrogen		The first element on the periodic table, which is highly combustible, colourless, odourless, and emissions-free in its gaseous form
Liquified natural gas	LNG	Natural gas that has been cooled to a liquid form for ease of transport. Made up of predominantly methane, natural gas is what services residential and industrial gas heating as well as gas-fired power stations
Steam methane reformation	SMR	Also referred to as grey hydrogen, the most commonly used hydrogen production method, which uses natural gas and steam as inputs
Coal gasification		Also referred to as brown hydrogen, a hydrogen production method using coal, water, and air as inputs
Carbon capture and storage	CCS	Necessary to create blue hydrogen, technology which prevents fossil fuels from releasing carbon dioxide into the atmosphere, usually by capturing carbon and storing it underground geological formations
Autothermal reforming	ATR	An alternative method of producing hydrogen from natural gas which allows for higher carbon capture rates
Electrolysis		Also referred to as green hydrogen, a process which uses electricity to split water into its separate hydrogen and oxygen components
Electrolyser		The electrical component required for electrolysis
Alkaline electrolyser	AE	Electrolyser technology which has historically been the most commercially viable
Polymer electrolyte membrane electrolyser	PEM	Electrolyser technology which has potential to become the cheapest available
Battery electric vehicle	BEV	A purely electric vehicle, powered by a rechargeable battery
Electrification		Replacing technologies that depend on fossil fuels with electricity, with the aim of using renewable electricity
Conversion loss		Loss of energy associated with converting a fuel from one state to another
Fuel cell		Used to power hydrogen vehicles and store hydrogen for energy usage, an electrochemical component which converts hydrogen into electricity
Hydrogen enrichment		The concept of mixing clean hydrogen with natural gas in order to reduce the carbon footprint of residential and industrial gas usage
Ammonia		A gas used in fertiliser and other products, which requires hydrogen as an input, and can also be used to transport hydrogen, or turn hydrogen into a fuel for vehicles
Industrial feedstock		A raw material or resource used in industrial production

Part 1: Understanding Hydrogen & Australia's Hydrogen Opportunity

Key Points

1. *Hydrogen is emerging as a fuel of the future. It is emissions-free when burned, and can replace traditional uses of fossil fuels in heavy industry such as natural gas.*

2. *There are three primary types of hydrogen: green, where renewable energy is used to produce hydrogen; blue, where fossil fuels are used to produce hydrogen but emissions from the process are captured; and grey or brown, where fossil fuels are used to produce hydrogen, but the emissions are not captured.*

3. *Achieving scale in the production of hydrogen quickly will be critical if Australia is to capitalise on its advantages in hydrogen production.*

Hydrogen, in its gaseous form, is highly combustible, colourless, odourless, and emissions-free. These properties make hydrogen an attractive solution to the problem of reducing the world's dependence on fossil fuels. However, despite being the most abundant element in the universe, hydrogen cannot be directly captured from nature, and must be produced using some form of energy.

A number of possible methods are available to produce hydrogen, which vary in their emissions intensity and cost. Since hydrogen produced using low-emissions methods can be used in a variety of applications such as energy, heating, transport, and industrial production, considerable support for low-emissions hydrogen has emerged from both government and businesses aiming to reduce Fretaintheir carbon footprint. The merits of these various uses of hydrogen are discussed further in Part 2 of this report.

The predominant methods of hydrogen production at present are steam methane reformation (SMR) and coal gasification. These methods, commonly referred to as "grey" and "brown" hydrogen respectively, use natural gas and coal as inputs. By burning fossil fuels, these processes create carbon dioxide emissions, unless carbon capture and storage (CCS) is used in conjunction with them to create low-carbon "blue" hydrogen.

Blue hydrogen generation offers the opportunity to decarbonise current hydrogen production while largely retaining its current fuel sources and industrial processes. Being able to utilise existing coal and gas network infrastructure helps keep production costs down, which proponents cite as a key benefit of adopting blue hydrogen.[1]

[1] Global CCS Institute (2021), *Global Status of CCS 2021*, Global CCS Institute, p. 57

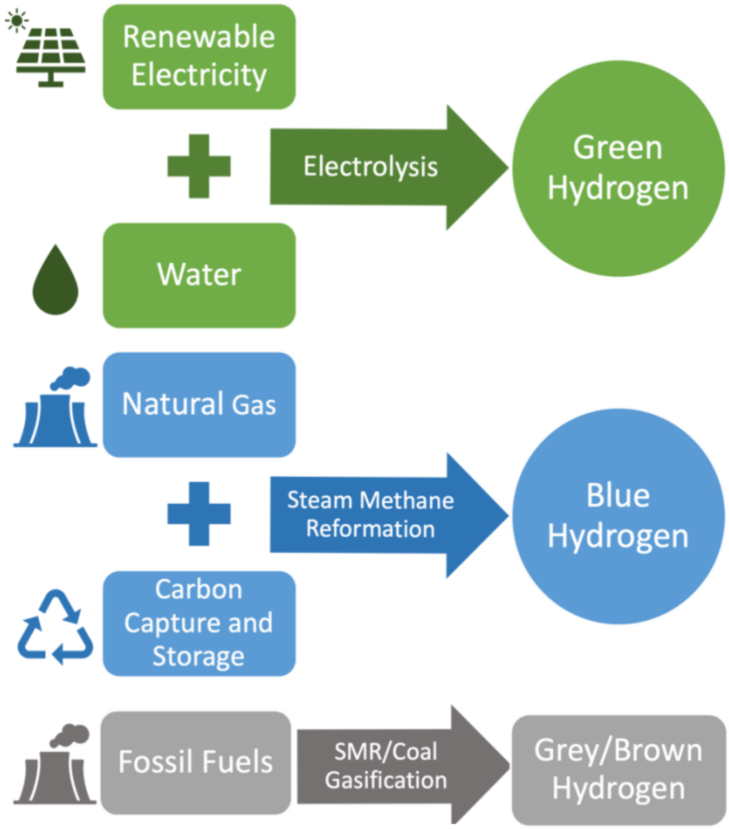

Figure 1: The hydrogen colour system

Alternatively, "green" hydrogen can be produced using a process called electrolysis, which has existed for more than 200 years. It works by using electricity to split water into its hydrogen and oxygen components. The key piece of technology which facilitates this is called an electrolyser. Given the only outputs from this process are hydrogen and oxygen, if the electricity used to power the electrolyser is generated from renewable resources, then the entire process is emissions-free.

There are a number of green hydrogen projects in Australia which are either planned or under construction. Of these operational projects, four involve mixing hydrogen into gas networks, four involve using hydrogen as a form of energy generation or storage, and four involve mobility applications (mainly transport and refuelling).[2]

The effectiveness of carbon capture and storage technology is uncertain

Blue hydrogen is an attractive option – the Australian Federal Government has flagged a broad 'clean hydrogen' strategy, where both green and blue hydrogen with substantial CCS are supported.[3] However, the effectiveness of CCS in practice is subject to some uncertainty.

[2] CSIRO (2022), *Hydrogen Map*, https://www.csiro.au/en/work-with-us/use-our-labs-facilities/Hydrogen-Map#markerName=Sir%20Samuel%20Griffith%20Centre

[3] Australian Government (2021) *Australia's National Hydrogen Strategy,* https://www.industry.gov.au/data-and-publications/australias-national-hydrogen-strategy

Using steam methane reformation (SMR), which is currently the most widely used grey hydrogen production method, it is technologically feasible to capture 90% of emissions. Autothermal reforming (ATR) technology is an alternative method which produces more concentrated carbon emissions; 95% or more of the emissions from this process can be captured. However, these upper estimates for capture rates using both methods are yet to be demonstrated in practice.[4]

The International Energy Agency (IEA) reports 16 operational blue hydrogen projects in the world, 10 of these being at a commercial scale.[5] There is only one operational CCS project in Australia – the Gorgon Gas Plant operated by Chevron. This project does not involve hydrogen production, and over the first five years of its operation, reported a capture rate of 68%, short of its targeted 80%.[6]

However, research and development into CCS technology is taking place. The Global CCS Institute reported in September 2021 that in addition to the 27 commercial-scale operational CCS facilities around the world, 106 were either under development or construction, and that 71 of these were undertaken in the first nine months of 2021. While theoretical carbon capture rates are yet to be demonstrated in blue hydrogen production, this volume of new CCS projects may well achieve these targets in coming years.

The lifecycle emissions of blue hydrogen production need to be considered

Even with effective CCS, greenhouse gas emissions still take place at other points in the blue hydrogen lifecycle. In particular, methane which is 30 times more potent than carbon dioxide in terms of contribution to the greenhouse effect, leaks throughout the gas transportation process.[7] Methane leakage is already an issue for industrial users of gas. However, the issue must also be considered in the development of supply chains for a low-emissions product.

Estimates of the emissions intensity of blue hydrogen vary according to the extent to which they factor in this issue.[8] Incorporating lifecycle emissions, the theoretical capture range for

[4] IEA (2021), *Global Hydrogen Review*, IEA, p. 129
[5] IEA (2021), *Global Hydrogen Review*, IEA, p. 130
[6] Readfearn (2021), *Australia's only working carbon capture and storage project fails to meet target*, The Guardian, https://www.theguardian.com/australia-news/2021/nov/12/australias-only-working-carbon-capture-and-storage-project-fails-to-meet-target
[7] Myhre, G. et al. (2013), *Anthropogenic and Natural Radiative Forcing*, in Stocker, T. (eds.), Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, p. 731
[8] Global CCS Institute (2021), *Global Status of CCS 2021*, Global CCS Institute, p. 55

lifecycle carbon and methane emissions in hydrogen production ranges from approximately 55% using current industrial practices, to near-complete (99.9%).[9]

Blue hydrogen is currently cheap to produce, but scope for further cost reductions is limited

Advances in CCS technology may increase carbon capture rates, but may not have a marked effect on the cost of producing blue hydrogen, due to CCS being 'embedded in the hydrogen extraction and purification process'.[10] The main factors driving the cost of blue hydrogen are the cost of the fuel inputs, and the scale of production plants.

Coal and gas have been historically both widely available and affordable in Australia, due to extensive network infrastructure and many of the capital expenditure costs required for their production having been recovered. This is a key contributor to recent CSIRO estimates for the cost of blue hydrogen being as low as $2.27/kg using SMR and $2.57/kg using black coal gasification, which is close to being competitive with brown and grey hydrogen.[11]

However, future uncertainty around the cost of fossil fuels, particularly in light of recent geopolitical instability which caused large increases in gas prices, may lead to blue hydrogen costs increasing. This, together with likely cost reductions in renewable energy used for green hydrogen production (discussed further in section 3), poses the risk of blue hydrogen investments becoming 'stranded assets'.[12]

Blue hydrogen costs can be minimised only by increasing scale

The greatest scope for reduction in the cost of blue hydrogen is through scale effects brought about by increasing plant size and network efficiency. Expanding the size of production plants would reduce average fixed costs, and developing hydrogen transportation technology and infrastructure would reduce the need for hydrogen production sites to be co-located with end-uses.[13]

The hurdle in attaining these economies of scale (which also faces green hydrogen production) however, is a 'chicken-and-egg' problem between hydrogen producers and potential users. Large-scale investment in hydrogen production won't take place until demand is sufficiently large, but demand won't be sufficiently large until hydrogen cost has fallen due to large-scale production.

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[9] Zhou, Y. et al. (2021), *Life-cycle Greenhouse Gas Emissions of Biomethane and Hydrogen Pathways in the European Union*, ICCT, p. iii
[10] Bruce, S. et al. (2018), *National Hydrogen* Roadmap, CSIRO, p. 20
[11] Bruce, S. et al. (2018), *National Hydrogen* Roadmap, CSIRO, p. 20
[12] IRENA (2020), *Geopolitics of the Energy Transformation*, IRENA, p. 93
[13] Bruce, S. et al. (2018), *National Hydrogen* Roadmap, CSIRO, p. 17

The factors driving the cost of green hydrogen are undergoing rapid change

Despite demonstrated technical feasibility, the key factor preventing wide adoption of green hydrogen production is the cost involved. It is currently more expensive to produce hydrogen via electrolysis than it is using fossil fuels, although this cost landscape is a dynamic one.

Developments in electrolyser technology are likely to affect the cost of green hydrogen. While alkaline (AE) electrolysers have to date been the most commercially viable, it is expected that newer polymer electrolyte membrane (PEM) electrolysers, which have the potential to reduce green hydrogen costs, will soon be the more competitive option.[14]

The main driver of green hydrogen cost, however, is the cost of the renewable electricity used in its production.[15] In Australia, this has fallen significantly over the last decade, and further cost reductions are predicted.[16] The extent of these cost reductions will in part depend on the wider energy strategy that is pursued in Australia.

Upfront capital expenditure on generation and network infrastructure (transmission and storage) plays a significant role in renewable electricity cost. With a limited existing renewable network to connect to, individual green hydrogen projects will have to incur these capital expenditure costs, making it hard to compete financially with fossil fuel hydrogen projects which are well serviced by the existing energy grid.

If, however, renewable generation and network infrastructure are already widespread (as part of Australia's strategy to decarbonise the electricity sector), the cost of sourcing electricity will become less of a hurdle for the viability of green hydrogen. The newly elected federal government's Powering Australia Plan has signalled important funding measures to help develop this network infrastructure.[17]

Like blue hydrogen, increasing scale is necessary to minimise the cost of green hydrogen

After electricity cost, the other main determinants of green hydrogen costs are scale effects similar to those which affect blue hydrogen costs.[18] Increasing the size of green hydrogen production plants, increasing the capacity utilisation of electrolysers, and expanding transportation infrastructure, all result in reductions in the per-kilogram cost of green hydrogen. These capacity and scale effects can only be attained by increasing production, which in turn will require cheap and widely available renewable electricity, as outlined above.

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[14] Bruce, S. et al. (2018), *National Hydrogen* Roadmap, CSIRO, p. 13
[15] IRENA (2020), *Green Hydrogen Cost Reduction*, IRENA, p. 8
[16] Longden, T. et al. (2020), *Green hydrogen production costs in Australia: implications of renewable energy and electrolyser costs*, ANU CCEP Working Paper 20-07, p. 6
[17] Australian Labor Party (2021), *Powering Australia,* https://www.alp.org.au/policies/powering-australia
[18] Bruce, S. et al. (2018), *National Hydrogen Roadmap*, CSIRO, p. 14

With the above sources of cost reduction taken into account, the CSIRO has estimated that the costs of green hydrogen using 'PEM and AE could be reduced to $2.29-2.79/kg and $2.54-3.10/kg respectively'.[19] Realising these costs would make green hydrogen competitive with alternative hydrogen production methods, while creating fewer emissions.

[19] Bruce, S. et al. (2018), *National Hydrogen Roadmap*, CSIRO, p. 19

Part 2: Examining the Demand for Hydrogen

Key Points

1. *Hydrogen is already used widely in industrial applications, and there are a number of other future possibilities for hydrogen utilisation.*

2. *Despite some of these potential uses not being the most efficient long-term method of decarbonising their respective industries, they should remain in consideration for the short-term scaling up of the Australian hydrogen industry.*

While the majority of current hydrogen demand is generated by specific industrial uses, there is a range of other potential applications which are technically feasible. With the availability of blue or green hydrogen, many of these applications would present opportunities to de-carbonise some of Australia's most emissions-intensive industries, such as transport and energy.

Global hydrogen consumption in 2020 was 90 Mt – almost all of which was used for either oil refining, or as an industrial feedstock.[20] Less than 5 Mt was produced using low-carbon technology. Under the IEA's 'NetZero by 2050' scenario, this demand would grow to over 200 Mt by 2030, and over 500 Mt by 2050, with the majority of this hydrogen being low-carbon.[21]

Any analysis of the long-term suitability of hydrogen for industrial applications should examine alternative solutions to the same decarbonisation problem. In some instances, electrification can provide a solution that is more efficient in terms of cost and emissions. Notwithstanding, some applications which are not optimal in the long-term may provide the opportunity for the rapid expansion of the domestic hydrogen industry.

While this section describes each application of hydrogen and its merits at a summary level, further detail evaluating the long-term efficiency question is provided in the appendix.

Oil Refining

The largest single use for hydrogen in 2020 was oil refining, making up 41% of total demand. Substituting blue or green hydrogen for carbon-intensive hydrogen production methods in this context would be a clear avenue through which emissions reduction could take place. It is important to note here that the extent of the emissions reduction will likely be limited by the fact that global oil demand itself will decrease as renewable alternatives proliferate.

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[20] IEA (2021), *Hydrogen*, IEA, https://www.iea.org/reports/hydrogen
[21] IEA (2021), *Global Hydrogen Review*, IEA, p. 44

However, the CSIRO has suggested that hydrogen could also play a role in treating renewable fuels, such as those derived from biomass.[22]

Industrial Feedstocks

The other main contributor to existing hydrogen demand is as an industrial feedstock, i.e. using hydrogen directly as a raw material in production. The most prominent of these is ammonia production, which is used to make fertiliser, and was responsible for 36% of total hydrogen demand in 2020.[23] Given its widespread requirement in the agricultural industry, ammonia is expected to become one of the largest sources of demand for clean hydrogen.[24]

Hydrogen is also used as a raw input into other products such as methanol, glass, and food products like margarine. While these applications consume comparatively less hydrogen than ammonia production, they still present important opportunities to replace brown or grey hydrogen with clean alternatives. In total, industrial feedstocks made up 57% of total hydrogen demand in 2020. Given that hydrogen is an essential input into these processes, these are the applications which currently have the most scope for clean hydrogen to play a role in emissions reduction.

Electricity Generation and Storage

Being responsible for more greenhouse gas emissions than any other sector in Australia, electricity generation is a priority for de-carbonisation. Hydrogen can be used to generate electricity either by being converted into fuel cells, or creating heat which powers gas turbines. If clean hydrogen is used in either of these methods, the end electricity created would be considered renewable.

In countries with sufficient renewable generation capacity, the loss of energy associated with converting renewable electricity into green hydrogen and then back again, means it would be more efficient in terms of both energy use and cost, to use the renewable electricity directly.[25] This is the case in Australia, where there is an abundance of potential solar and wind generation, as well as open space to house renewable infrastructure.

However, countries without these natural endowments will need to import their renewable electricity, and converting Australian renewable electricity to hydrogen for generation is a means of achieving this.

22 Bruce, S. et al. (2018), *National Hydrogen Roadmap*, CSIRO, p. xviii
23 IEA (2021), *Hydrogen*, IEA, https://www.iea.org/reports/hydrogen
24 Department of Industry, Science, Energy, and Resources (2021), *State of Hydrogen*, Australian Government, p. 12
25 Bruce, S. et al. (2018), *National Hydrogen* Roadmap, CSIRO, p. 35

While electricity generation is not likely to be a major source of hydrogen demand in the long-run in Australia, hydrogen does have the potential to play a role in the development, scaling and integration of storage, which is one of the central challenges involved with the transition away from fossil fuels.

Coal and gas-fired power plants can theoretically operate at any time, providing a degree of reliability and certainty for the energy grid – particularly in providing 'peaking' capacity. Renewable generation, on the other hand, can only take place at certain times of the day, or in some cases, months of the year, when the relevant source of energy (the sun or the wind) is available. This means that significant storage infrastructure is required if electricity grids are to be reliably powered by renewables.

At present, the most common form of energy storage is batteries. As of April 2022, a total of 47,672 batteries have been installed for use with small-scale (mostly residential) solar energy systems in Australia,[26] and a number of large-scale batteries are either in operation or under construction.[27] The downside to batteries, however, is that the timeframe within which they can discharge their stored energy is usually a matter of hours. This means that batteries work well at stabilising the daily fluctuations in renewable energy availability, but are unable to deal with prolonged or seasonal fluctuations.[28]

Clean hydrogen on the other hand, which can be considered an alternative form of 'stored' renewable energy, has a storage timeframe which would stabilise renewable generation over the longer-term. 'Stationary' hydrogen fuel cells can also be used to provide backup power for potential outages.[29] The Sir Samuel Griffith Centre at Griffith University, which uses solar generation to operate independently of the energy grid, demonstrates the feasibility of using batteries and stationary hydrogen in tandem to service short-term and long-term energy storage needs.[30]

[26] Clean Energy Regulator (2022), *Postcode data for small-scale installations*, Australian Government, http://www.cleanenergyregulator.gov.au/RET/Forms-and-resources/Postcode-data-for-small-scale-installations
[27] Clean Energy Council (2021), *Energy Storage,* Clean Energy Council, https://www.cleanenergycouncil.org.au/resources/technologies/energy-storage
[28] Steilen, M. and Jorissen, L. in Mosely, P. T. and Garsch, J. (eds.) (2015), *Electrochemical Energy Storage for Renewable Sources and Grid Balancing*, Elsevier, p. 144
[29] IEA (2021), *Global Hydrogen Review*, IEA, p. 100
[30] CSIRO (2020), *Sir Samuel Griffith Centre*, CSIRO HyResource, https://research.csiro.au/hyresource/sir-samuel-griffith-centre/

Case Study: The Sir Samuel Griffith Centre

Griffith University's Sir Samuel Griffith Centre is a unique showcase of how a large building's power needs can be met entirely with renewable electricity, by using both batteries and hydrogen as energy storage. Onsite solar panels generate electricity when the sun is shining, and any generation in excess of demand is used to recharge the building's 1024 lithium-ion batteries, and power an electrolyser to create hydrogen. The batteries are used to service short-term energy demand when solar generation stops at night. Then, when there are any prolonged shortfalls in generation, due to bad weather events for example, the hydrogen is converted into fuel cells and used to service this long-term demand.

Transport

Following electricity generation, the transport sector is Australia's next-largest contributor to greenhouse gas emissions. An element of decarbonising this sector, particularly in cities, revolves around the redesign of transport infrastructure and incentives, in order to encourage environmentally friendly modes of transport such as public transport, cycling, and walking.[31] However, many current transport uses are essential for the functioning of Australia's economy, and in these cases emissions reduction can only take place through the use of alternative fuels, such as clean hydrogen or renewable electricity.

For cars and other light vehicles, battery electric vehicles (BEVs) have already seen much wider uptake than hydrogen-fuelled cars due to the same underlying conversion loss issue that inhibits hydrogen as a source of energy generation.

With larger and heavier road vehicles, the efficiency advantages of BEVs are less clear cut as the range and physical size of batteries become an issue. This has resulted in some interest and investment in hydrogen-powered heavy vehicles for industrial purposes, while the truck and bus industries have so far leant towards the BEV alternative.[32]

With shipping and aviation, the size and range issues of batteries makes them nearly impossible to use, meaning that hydrogen, in the form of either fuel cells or ammonia, may be necessary to decarbonise these industries.

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[31] Climate Council (2018), *Waiting for the Green Light: Transport Solutions to Climate Change*, p. 27

[32] See appendix 5.3

Mixing with gas and heating

Owing to its ability to be readily implemented, a frequently suggested application of hydrogen is integration into the existing gas network, also known as hydrogen enrichment. This would involve using clean hydrogen, a gas itself, to either replace, or mix in with the natural gas (predominantly methane) which is currently used for a range of residential and industrial heating purposes.

Hydrogen enrichment is one of the more immediate possible applications of clean hydrogen, and can therefore play a role in transitioning heating away from fossil fuels. However, it should not be used to lock in household gas use in the long-run when electrification alternatives are available.[33] A more than 20% hydrogen mix in the gas network would be incompatible with both current network infrastructure and household and industrial appliances, and would pose potential safety risks. Furthermore, the energy and emissions efficiency of hydrogen enrichment is significantly lower than the alternative of electric heat pumps.

While electric heat pumps offer a promising alternative to gas for households in the long-run, replacing the entire stock of gas heating and cooking equipment in households will take significant time. A hydrogen-gas mix therefore offers a short-term emissions advantage.

Manufacturing

There are several technologies that would allow emissions-intensive manufacturing processes to substitute clean hydrogen for the fossil fuel inputs they currently use in production. In steel manufacturing, for example, hydrogen can replace the carbon-rich gases that are currently used for iron ore reduction and heating blast furnaces.[34] Although the technology required for this is not likely to exist at a commercial scale until the 2030s, it represents an important opportunity for the steel industry to significantly reduce its emissions.[35]

Similarly, clean hydrogen can displace gas as the fuel used for high temperature heating in aluminium manufacturing (although low and medium temperature heating are better suited to electrification).[36] Although only nascent technology, hydrogen can also be used in cement production – combusting fuel using the oxygen by-product from green hydrogen, instead of the current approach which uses air, would reduce nitrous oxide emissions.[37]

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[33] See appendix 5.4
[34] IEA (2021), *Global Hydrogen Review*, IEA, p. 59
[35] Bruce, S. et al. (2018), *National Hydrogen Roadmap*, CSIRO, p. 52
[36] Sandstrom, J. et al. (2021), *Closing the gap for aluminium emissions*, Mission Possible Partnership, p. 13
[37] Nhuchhen, D. R. (2022), *Decarbonization of cement production in a hydrogen economy*, Applied Energy, 317

All of the industries listed here are currently large contributors to Australia's greenhouse gas emissions.[38] With the necessary advancements in technology and commercial feasibility, clean hydrogen could play a crucial role in reducing these emissions.

Export

In this section, the discussion has largely been framed within an Australian context. Australia has a vast endowment of potential renewable energy supply compared to other nations, which means that electrification is often more feasible than it is elsewhere. Beyond natural constraints, other factors which are different across countries, such as the state of existing network infrastructure, may also mean that hydrogen use is more advantageous overseas than it is here. Given Australia's natural comparative advantage in green hydrogen production, there is a significant opportunity to develop an export industry servicing countries with strong clean hydrogen demand.[39]

The only barrier to the development of such an industry is the actual transportation of hydrogen internationally. At present, the cheapest method for transporting hydrogen is having it compressed and run through pipelines, as demonstrated by existing projects in Europe.[40]

Exporting hydrogen from Australia, however, necessitates transport via sea, in which case the hydrogen must be liquified, rather than compressed.[41] This process is slightly more expensive, and although not currently commercially viable, feasibility has been demonstrated by a recent successful shipment of liquified hydrogen from the port of Hastings in Victoria, to the port of Kobe in Japan.[42] Other research has also suggested that by 2050 the international transport of hydrogen could be conducted through ammonia conversion.[43]

With further technological developments, export demand has the potential to be a lucrative use of clean hydrogen produced in Australia. Yet the export opportunity is not limited to hydrogen itself – it also includes the potential to export any manufactured goods that utilise clean hydrogen as an input, such as steel, aluminium, and cement.

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[38] Wood, T. et al (2022), *The next industrial revolution,* Grattan Institute, p. 6
[39] IEA (2021), *Global Hydrogen Review*, IEA, p. 126
[40] EU Joint Research Centre (2021), *Assessment of Hydrogen Delivery Options*, European Commission
[41] Bruce, S. et al. (2018), *National Hydrogen Roadmap*, CSIRO, p. 36
[42] HESC (2022), *Successful Completion of Pilot Project Report*,
https://drive.google.com/file/d/127L2epevYr7XNEx2XEY-iI05x9llL-A1/view
[43] DNV (2022), *Hydrogen Forecast to 2050*, DNV, p. 6

Part 3: The First Mover Opportunity

Key Points

1. *Australia has plans to be a green hydrogen exporting economy in the 2030s. To facilitate this medium-term ambition, work needs to be done today to increase the scale of hydrogen production.*
2. *The economic benefits of scale achieved by expanding blue hydrogen production are likely transferrable to green hydrogen.*
3. *Utilising hydrogen as an industrial feedstock in Australia this decade could provide a competitive advantage for Australian manufacturers, and enable the emergence of a competitive renewable energy manufacturing sector in Australia this decade.*

Part 2 outlined an ideal long-term scenario in which the potential key applications of hydrogen were exports, shipping and aviation, long-term energy storage, and impossible-to-electrify domestic industries. To meet this aspiration for Australia's hydrogen industry, we will require both blue and green hydrogen production in the short-run in order to scale up the hydrogen industry.

Scale effects are transferable between blue and green hydrogen

The opportunity for Australia to become the global leader in hydrogen exports can only be taken advantage of if this scaling up of industry takes place with urgency. With multiple countries endowed with the resources necessary to be leading clean hydrogen exporters, it is essential that Australia is able to produce hydrogen at low cost. As discussed in part 1 of this report, the key path to achieving cost reduction is through expanding the scale of production.

Many of these scale effects are transferrable between green and blue production technologies, so a short-run approach which focuses on expanding the clean hydrogen industry as a whole, rather than preferencing either technology, maybe the quickest way to achieve this.

Reducing hydrogen production costs quickly is key

Green hydrogen will likely not have a clear cost advantage over blue until 2030, once renewable energy costs have fallen.[44] Until this is the case, and as long as there is uncertainty surrounding the costs of both technologies, the adoption of either green or blue hydrogen should be encouraged wherever they are the most commercially viable. This focus on expanding scale and reducing production costs as rapidly as possible will ultimately best position Australia to become a hydrogen export leader.

A rapid increase in scale will not only require an agnostic approach to production technology, but also the establishment of significant domestic hydrogen demand. While becoming an export leader is a key objective, exporting hydrogen is not currently technologically possible at a commercial scale, for reasons discussed above. Therefore, the immediate expansion of hydrogen supply needs to come off the back of local demand.

Moving first on hydrogen will create a renewable manufacturing advantage

Expanding the domestic hydrogen industry also creates the potential to strengthen Australia's manufacturing sector. The economic opportunities exist here in green manufacturing industries which use hydrogen as an input, as well as the expansion of the hydrogen industry itself.

The scaling up of Australia's clean hydrogen industry, and the renewables sector more broadly, will require an enormous amount of new capital goods. Hydrogen production equipment and transportation infrastructure, CCS facilities, ports and shipping infrastructure, and renewable energy generation and network infrastructure, all need to be supplied in order to realise the ambitions of a hydrogen export economy.

The installation, construction, and rollout of this infrastructure will provide a much-needed stimulus to employment in the resources sector as fossil fuel jobs decline. It is also important however, that Australia maximises this stimulus by manufacturing these capital goods domestically as well.

With hydrogen or gas being a necessary input into the manufacture of various industrial goods, having low-cost hydrogen available through large-scale domestic production would enable these goods to be produced cheaply in Australia (and to reduce emissions in those industries that currently rely on coal or gas). As well as strengthening existing manufacturing industries such as ammonia production, low-cost domestically produced hydrogen would

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[44] Longden, T. et al. (2020), *Green hydrogen production costs in Australia: implications of renewable energy and electrolyser costs*, ANU CCEP Working Paper 20-07

help establish the new clean industrial processes outlined in part 2, such as green steel, aluminium, and cement production.

Developing these manufacturing industries would also mean that the hydrogen export opportunity expands, from simply revolving around hydrogen itself, to including the export of value-added goods that utilise Australian hydrogen in their production. The size of the export market for these green manufactured goods will continue to increase as NetZero commitments proliferate and global demand shifts towards cleaner production processes – for example, under the IEA's 'announced pledges' scenario, demand for steel utilising clean hydrogen increases fivefold by 2050.[45]

A crucial problem for Australia's energy transition is creating blue-collar jobs in low-carbon industries. Many of the 'renewable jobs' which are often advocated for involve the establishment of renewable technology and infrastructure, but provide little prospects for longer-term employment in green industries.

The strengthened manufacturing sector described here, created by producing cheap hydrogen at a large scale domestically, would provide long-term, low-carbon employment for Australian blue-collar workers. Greater domestic production of industrial goods would also insulate Australia against the international supply chain shocks which it is currently exposed to due to a dependence on imports.

Acting as a first mover into scaling up hydrogen production will not only put Australia in position to become a global hydrogen export leader, but it will also generate economic benefits through an enlarged manufacturing sector. Conversely, if Australia fails to act quickly in establishing cheap domestically produced hydrogen, it risks losing not only these opportunities, but also the existing industries which depend on hydrogen as an input.

[45] IEA (2021), *Global Hydrogen Review*, IEA, p. 59

Part 4: Australia's Current Approach to Hydrogen

Key Points

1. *States and the Commonwealth Government have begun to implement policies and strategies aimed at guiding the development of the hydrogen industry.*

2. *The 2019 National Hydrogen Strategy, chaired by Dr. Alan Finkel, outlined the potential for 'clean hydrogen', a technology-neutral definition which encompasses both green hydrogen and blue hydrogen with proven CCS.*

3. *There are live projects underway today in Australia producing hydrogen, such as the Hydrogen Energy Supply Chain project in the La Trobe Valley.*

A number of policies which support the expansion of Australia's hydrogen industry have been announced at both the federal and state level. While the implementation of many of these policies is still underway, it is clear nonetheless that developing a strong hydrogen industry is a priority at multiple levels of government.

Policy at the federal level

The Australian Government has earmarked the hydrogen industry and the use of CCS as 'critical to Australia's technology led approach to reducing emissions'.[46] Australia's *National Hydrogen Strategy* was published in 2019, and seeks to 'take advantage of increasing global momentum for clean hydrogen and make it our next energy export'.[47] The path to achieving this in the strategy is establishing low-cost hydrogen production via the scale effects discussed in part 1 of this report.

The main pillar of the strategy is the use of hydrogen hubs - 'clusters of large-scale demand' which aim to bring about these scale effects and push down costs. The government has so far announced $464 million for hydrogen hub project grants. While the export market for hydrogen is still in a developmental phase, the aforementioned large-scale demand will need to be composed of domestic uses in the short-term.

Given that many of the candidates and/or recipients of hydrogen hub grants are gas network operators, it is likely that hydrogen enrichment in gas networks will play a significant role in

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[46] Department of Industry, Science, Energy and Resources (2021), *Future hydrogen industry to create jobs, lower emissions and boost regional Australia*, Australian Government, https://www.minister.industry.gov.au/ministers/taylor/media-releases/future-hydrogen-industry-create-jobs-lower-emissions-and-boost-regional-australia

[47] COAG Energy Council (2019), *Australia's National Hydrogen Strategy*, Commonwealth of Australia, p. viii

establishing domestic demand.[48] To further enable this end-use, the government has also agreed to reform the national gas regulatory framework.[49]

We also note that all of the hydrogen hub implementation grants have so far been awarded to green rather than blue hydrogen projects.[50]

Aside from hydrogen hub grants, the federal government has made several other funding announcements which support the development of an Australian hydrogen industry. $300 million has been allocated to fund CCS projects, with a separate $300 million set aside for hydrogen research, development, and demonstration activities.[51]

Policy at the state level

Each of the state jurisdictions has published their own reports outlining a hydrogen strategy. While the specifics of each state's approach differ slightly, the overarching federal objective of increasing the scale of hydrogen production in order to push down costs and establish a long-term export industry is consistent in all of them.

The states also share a similar approach to the end-uses of hydrogen – while harnessing export demand is still the ultimate long-term aim, hydrogen enrichment, industrial feedstocks, electricity grid stabilisation, and transport, are all identified as key potential sources of short-term domestic demand.

One key difference, however, is where the national strategy adopts a technology-neutral approach in which 'clean hydrogen' is defined as both blue and green, the state strategies largely omit (with some exceptions) any explicit role for blue hydrogen production.

New South Wales published its *Hydrogen Strategy* in 2021, which includes further funding for hydrogen hubs, support for hydrogen research and development, and its own regulatory changes aimed at making investment in hydrogen projects more favourable.[52]

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[48] HyResource, *Australian Clean Hydrogen Industrial Hubs Program*, CSIRO, https://research.csiro.au/hyresource/australian-clean-hydrogen-industrial-hubs-program/
[49] Department of Industry, Science, Energy and Resources (2021), *Extending the national gas regulatory framework to hydrogen blends and renewable gases,* Australian Government, https://www.energy.gov.au/government-priorities/energy-ministers/priorities/gas/gas-regulatory-framework-hydrogen-renewable-gases
[50] HyResource, *Australian Clean Hydrogen Industrial Hubs Program*, CSIRO, https://research.csiro.au/hyresource/australian-clean-hydrogen-industrial-hubs-program/
[51] Department of Industry, Science, Energy and Resources (2021), *State of Hydrogen,* Australian Government, p. viii
[52] Department of Planning, Industry, and Environment (2021), *NSW Hydrogen Strategy*, NSW Government, pp. 9-11

It is the only state which directly addresses the lack of a role for blue hydrogen in its strategy, on the basis that 'by the time blue hydrogen production is operational in NSW, it is unlikely to have a price advantage over green hydrogen. Hydrogen production forecasts expect green hydrogen to be competitive with blue hydrogen around 2030'.[53]

Victoria published its *Renewable Hydrogen Industry Development Plan* in 2021, with a particular focus on developing the skills and training necessary to underpin a hydrogen industry.[54] The use of hydrogen in the gas network is identified as a key application of hydrogen given the state's extensive gas network.

This published plan only deals with green hydrogen production, although Victoria's flagship hydrogen project involves a plan to export blue hydrogen to Japan. As referenced in part 2 of this report, the Hydrogen Energy Supply Chain project has recently demonstrated the successful shipment of hydrogen to the Port of Kobe. The hydrogen in question was produced using Latrobe Valley coal, with plans in place for a CCS facility to be installed at the production site so the hydrogen is blue rather than brown.

Queensland published its *Hydrogen Industry Strategy* in 2019, which also focuses on education and training in the hydrogen industry, and outlines a 'pro-business approach'.[55] This includes the state's Hydrogen Investor Toolkit, and funding assistance to several large-scale private sector hydrogen projects.

The strategy highlights the state's existing resource export infrastructure and proximity to Asia as factors which will enable an export industry in the long-run. While the strategy focuses on green hydrogen, it acknowledges the potential role of blue hydrogen as a transition fuel.

South Australia published its *Hydrogen Action Plan* in 2019, with a strong emphasis on green hydrogen production given the state's renewable energy generation capacity.[56] More recently, the South Australian government announced its landmark Hydrogen Jobs Plan, a $593 million government-operated hydrogen power station, electrolyser, and storage facility.[57]

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[53] Department of Planning, Industry, and Environment (2021), *NSW Hydrogen Strategy*, NSW Government, p. 15

[54] Department of Environment, Land, Water, and Planning (2021), *Renewable Hydrogen Industry Development Plan*, Victorian Government

[55] Department of State Development, Manufacturing, Infrastructure, and Planning (2019), *Queensland Hydrogen Industry Strategy*, p. 10

[56] Department for Energy and Mining (2019), *South Australia's Hydrogen Action Plan*, Government of South Australia

[57] Department for Energy and Mining (2022), *Hydrogen Jobs Plan*, Government of South Australia, https://www.energymining.sa.gov.au/industry/modern-energy/hydrogen-in-south-australia/hydrogen-jobs-plan

South Australia has also signed an international export memorandum of understanding with the Port of Rotterdam in the Netherlands. This involved conducting a feasibility study that showed that South Australian hydrogen could supply up to 10% of Rotterdam's hydrogen requirements in 2050.[58]

Western Australia published its *Renewable Hydrogen Strategy* in 2021, which, like Queensland's strategy, emphasises the potential for a thriving hydrogen export industry given the state's existing resources infrastructure.[59] The Western Australian government has also announced further funding for hydrogen hubs, as well as an additional $61.5 million to support the development of a green hydrogen industry in its 2021-22 budget.[60]

While Western Australia's hydrogen strategy makes no mention of blue hydrogen or CCS, the state is home to the only functioning CCS operation in Australia – the Gorgon Gas Plant, as mentioned in Part 1 of this report.

Tasmania published its *Renewable Hydrogen Action Plan* in 2020, which includes $50 million in support for green hydrogen projects. [61] The plan focuses on the Bell Bay Advanced Manufacturing Zone as a key technological cluster which can be used to scale up the hydrogen industry, particularly through the production of green ammonia.

Case Study: The Latrobe Valley Hydrogen Energy Supply Chain Project

The Hydrogen Energy Supply Chain (HESC) project, situated in Victoria's Latrobe Valley, is a pilot project currently producing hydrogen using coal, with further plans for CCS facilities in order to produce blue hydrogen. Its primary purpose, however, is to 'demonstrate an integrated hydrogen supply chain, encompassing production, storage and transportation and delivering liquefied hydrogen to Japan'.[62] As part of this demonstration, HESC has constructed the first ever liquified hydrogen carrier ship, which, in early 2022, completed a successful shipment of hydrogen from Victoria to Japan.[63] This project represents the type that can help develop the infrastructure and supporting systems to accelerate the export of green hydrogen in the 2030s and beyond.

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[58] Department of Energy and Mining (2022), *Hydrogen export hubs*, Government of South Australia, https://www.energymining.sa.gov.au/industry/modern-energy/hydrogen-in-south-australia/hydrogen-export-hubs

[59] Department of Jobs, Tourism, Science, and Innovation (2021), *$61.5 million boost for WA's renewable hydrogen industry*, Government of Western Australia

[60] Government of Western Australia (2021), *$61.5 million boost for WA's renewable hydrogen industry*, Government of Western Australia

[61] Department of State Growth, *Tasmanian Renewable Hydrogen Action Plan*,

[62] CSIRO, 2022. 'Hydrogen Energy Supply Chian – Pilot Project'. https://research.csiro.au/hyresource/hydrogen-energy-supply-chain-pilot-project/

[63] HESC (2022), *Successful Completion of Pilot Project Report*, https://drive.google.com/file/d/127L2epevYr7XNEx2XEY-iI05x9llL-A1/view

Recommendations

Recommendation 1: The Australian Government should prioritise the expeditious scaling of hydrogen production this decade, irrespective of type, in order to maximise the opportunity for a clean hydrogen export economy to succeed in the 2030s and beyond.

For Australia to develop the supportive infrastructure, skilled workforce, transportation systems and customer relationships to enable green hydrogen exports in the future, governments need to work to scale the domestic hydrogen industry in the near-term. This would best be achieved by pursuing a technology neutral approach in the short-term, enabling blue hydrogen production to come online this decade to meet existing international demand. By scaling the production of hydrogen, private investment in the supportive infrastructure required by future hydrogen exporters is more likely to be realised, positioning Australia well at the turn of the decade.

Recommendation 2: The Australian government should explore ways to accelerate the use of hydrogen in existing industrial processes to support domestic renewable energy manufacturing.

Key to meeting Australia's ambitions as a renewable energy superpower is the development of a scaled domestic renewable energy powered manufacturing industry. While Australia is quickly embracing renewable technologies, the country's renewable energy manufacturing capacity remains nascent. Hydrogen offers an alternative energy source and feedstock to natural gas and coal. Working with industry, the Australian government and other key industrial stakeholders can collaboratively work towards a future in which existing industrial feedstocks, such as natural gas and coal, are largely replaced by more-affordable hydrogen. An abundance of cheap Australian hydrogen would allow local manufacturing to thrive in a NetZero world, and help Australian manufacturers maintain a competitive advantage in a global market. Developing this hydrogen market will also help Australia's domestic hydrogen industry scale this decade.

Recommendation 3: The Australian government should develop a Hydrogen Reservation Mechanism, safeguarding future industrial uses of hydrogen from domestic shortfalls during global energy shocks.

To ensure Australian industry is not adversely impacted by domestic hydrogen supply shortfalls in the future, the Australian Government should consider designing and legislating a national Hydrogen Domestic Reservation Mechanism during this term of parliament.

The 2022 global energy shock, ostensibly triggered by the rogue behaviour of a major petrostate, Russia, invading a neighbouring state, has caused substantial hardship for Australian energy consumers. This includes for industrial users, who rely on natural gas or coal to produce industrial outputs, including manufactured goods. As global energy prices skyrocketed through 2022, the structure of Australia's natural gas market created supply shortfalls in Australia, which led to significant energy price spikes for both household and industrial consumers. This occurred despite Australia begging the largest exporter of natural gas in the world, and came about as a result of the natural gas industry in much of Australia being free of any domestic reservation mechanism that safeguards supply for domestic consumption.

In Western Australia, a domestic gas reservation mechanism is in place, and has been since 2005. This mechanism has successfully reserved 15 per cent of the natural gas supply within the state, enabling local industry and household consumers to be somewhat inoculated from the extremes of the global energy market. The absence of such a mechanism in Australia's east coast gas markets has seen gas producers continue to export much of their natural gas output, seeking higher prices internationally, and effectively driving up the price of an increasingly scarce local supply.

Australian Governments can learn from the mistakes made in failing to sufficiently reserve Australia's gas outputs, and design a reservation mechanism for the emerging Hydrogen industry.

Such a mechanism should be designed in a way that it doesn't stifle investment and innovation in hydrogen production, but reserves a percentage of Australia's domestic hydrogen production when that production reaches a certain scale. To create certainty for industry, the Australian Government should consider pursuing a collaborative process during this term of parliament, allowing for legislation to be passed by 2025 that has buy-in from industrial producers and future users of hydrogen.

Conclusion

Australia has had an historic advantage when it comes to energy production. Rich in fossil fuels, Australia has been able to leverage this natural endowment into incredible wealth, while providing affordable energy to consumers until recent years.

But the changing global energy market requires Australia to get creative, and to position itself to capitalise on the emerging opportunities associated with the global transition towards net zero.

Hydrogen represents a major export opportunity for Australia, and also an opportunity to decarbonise domestic manufacturing within Australia in the coming decades.

This report has examined that opportunity, and argued that there is no time to waste if Australia is to capitalise on this historic opportunity.

Appendix: Evaluating the long-term efficiency of hydrogen applications in Australia

Part 2 outlined the various possible uses of hydrogen. However, the many industrial and household users of energy are likely to face a plethora of other options, including renewable electricity, storage such as battery and pumped hydro, and biofuels. Increasing domestic scale will best allow Australia to capture demand for hydrogen here and overseas, although this doesn't mean we should lose sight of what hydrogen usage looks like in an ideal long-term scenario.

There is significant variation in global hydrogen forecasts. While IEA estimates suggested that hydrogen demand in 2050 would be over 500 Mt, Deloitte analysis predicts it could still be less than 100 Mt under a scenario where rapid technological development in electrification occurs.[64] However, this latter outcome is not currently reflected in market announcements by the public and private sectors, which amount to at least 250 Mt of hydrogen in 2050.

The level of hydrogen demand which is released will in large part depend on how many of the proposed uses are actually adopted. This appendix provides further detail regarding the alternative applications of hydrogen discussed in part 2, to examine whether they are likely to provide long-term opportunities for an emerging Australian hydrogen industry.

5.1: Oil Refining and Industrial Feedstocks

As discussed previously, oil refining and industrial feedstocks are applications of hydrogen which already see wide usage, and cannot be electrified. Given clean hydrogen is the only available means of decarbonising these industries, the merit of using hydrogen here is clear-cut.

5.2: Energy Storage

Given battery technology predominantly allows for only short-term energy storage, as displayed in table 1, hydrogen can be used as a long-term storage solution to the inherent variability of renewable electricity generation.

[64] Deloitte (2019), *Australian and Global Hydrogen Demand Growth Scenario Analysis*, Deloitte, p. 4

Table 1: Energy Storage Properties

	Max power rating (MW)	Storage duration	Conversion efficiency
Lithium-ion battery	0.1 - 100	1 min - 8h	85 - 98%
Lead-acid battery	0.001 - 100	1 min - 8h	80 - 90%
NaS battery	10 - 100	1 min - 8h	70 - 90%
Flow battery	1 - 100	2-10h	60 - 85%
Hydrogen	0.01 - 1000	mins - weeks	25 - 45%

Source: Irany, R. et al. (2019), Energy Storage Monitor, *World Energy Council*, p. 11

It is clear that hydrogen has technical advantages over battery storage as an option for longer-term peaking requirements (for example, extended periods where renewable sources are not generating). However, when considering the use of hydrogen for this grid firming role, alternatives must still be examined given the underlying efficiency issues associated with hydrogen energy conversion.

Table 1 also reports a 25-45% conversion efficiency of hydrogen as a means of renewable energy storage. The data in this table is from 2015, yet despite significant research and development in the field in the time since, recent IEA estimates suggest that this round-trip efficiency is still only at 40%.[65] This is due to the inherent physical properties of hydrogen and the conversion process, meaning that technological advancements will not be able to raise this efficiency.

Hydroelectric dams can also play a role in stabilising the grid

A potential alternative for long-term storage is pumped hydro. Hydroelectric dams 'store' renewable energy by using the excess supply of power during peak generation times to pump water from a lower reservoir to up an upper reservoir. When demand needs to be serviced, the water from the upper reservoir is then released down through turbines which generate electricity. The round-trip energy efficiency of this process is between 70-85%, almost double that of stationary hydrogen.[66]

Important downsides to pumped hydro include high costs and potential negative ecological impacts. Australia is well-positioned to minimise the environmental effects due to its large endowment of potential pumped hydro sites, [67]which means low-impact sites, such as those which don't interact with river systems, can be chosen. [68] High costs are a more significant

[65] IEA (2021), *Global Hydrogen Review*, IEA, p. 101
[66] Environmental and Energy Study Institute (2019), *Fact Sheet: Energy Storage*, p. 3
[67] Department of Planning, Industry, and Environment (2020), *NSW Electricity Infrastructure Roadmap*, NSW government, p. 8
[68] Blakers et al. (2022), *Batteries get hyped, but pumped hydro provides the vast majority of long-term energy storage essential for renewable power – here's how it works*, The Conversation

issue however, due to the inherently capital-intensive nature of pumped hydro projects – this has been demonstrated recently by the Snowy Hydro 2.0 project, whose construction is projected to take over 10 years and has already cost more than $10 billion.[69]

The costs of hydrogen storage, on the other hand, vary. Storing pure hydrogen in underground salt caverns is relatively cheap,[70] whereas conversion to fuel cells requires precious metals and is therefore more expensive.[71] In a fast-changing research and technological environment, it is possible that the lower cost of hydrogen storage could outweigh the energy efficiency benefits of pumped hydro storage. Hydrogen should therefore remain a possible candidate for long-term storage and firming in an Australian electricity grid powered by renewables.

5.3: Transport

Whether battery-powered electric vehicles (BEVs) or hydrogen-fuelled vehicles are the more efficient solution to decarbonising the transport sector largely boils down to a trade-off between the greater energy efficiency of batteries against their size and weight. This trade-off varies significantly with the size and type of vehicle in question.

Low-carbon options for light vehicle transport are already available

Cars and light commercial vehicles make up over 60% of Australia's transport emissions, due to both higher per-capita car usage and higher emissions per vehicle than in comparable countries.[72] While clean hydrogen-powered vehicles using fuel cells have been touted as a potential replacement for carbon-emitting internal combustion engines, BEVs have already proven themselves as the more popular option. Development in BEV technology, infrastructure, and commerce, has rapidly outpaced that of hydrogen cars in recent years – in 2021 global BEV sales reached 6.6 million,[73] as opposed to just 15,500 for hydrogen cars.[74]

Hydrogen vehicles face the same conversion loss issue that hampers hydrogen energy storage. Where battery-powered cars utilise 80% of the electricity delivered to them, the process of converting electricity to hydrogen, then to fuel cells, which then powers a car, results in only 38% of the original electric power being retained.[75] While proponents of hydrogen cars cite the range and refuelling time of BEVs as a reason to adopt the former,

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[69] Woodley, T. (2022), *Five years on, Snowy 2.0 emerges as a $10 billion white elephant*, Sydney Morning Herald
[70] Londe, L. (2018), *Hydrogen caverns are a proven, inexpensive and reliable technology*, cH2ange
[71] Environmental and Energy Study Institute (2019), *Fact Sheet: Energy Storage*, p. 5
[72] Climate Council (2018), *Waiting for the Green Light: Transport Solutions to Climate Change*, pp. 6-12
[73] Paoli, L. and Gul, T. (2022), *Electric cars fend off supply challenges to more than double global sales*, IEA
[74] Munoz, J. F. (2022), *The Hydrogen Powered Car Is Alive: Sales Up By 84 Percent In 2021*, motor1.com
[75] Baxter, T. (2020), *Hydrogen cars won't overtake electric vehicles because they're hampered by the laws of science*, The Conversation

advancements in battery technology and the proliferation of BEV charging stations are expected to address these issues.

Trucks and heavy vehicles are also heading towards electrification

The choice between battery power and hydrogen power becomes more complicated in the context of larger vehicles – the size and weight of the batteries required reduces their energy efficiency (although it is still significantly higher than fuel cell engines), and compromises the available payload for trucks.[76] Given the long-haul nature of many heavy vehicle trips, the range issue mentioned above is also of more importance.

Fully electric buses are already in operation in multiple states around Australia,[77] [78] and the trucking industry both in Australia,[79] and abroad,[80] has thrown its support behind electric battery power over hydrogen power, citing the low energy efficiency and resulting high cost of the latter as a key factor. However, for larger heavy vehicles (such as those used in the mining and construction industries), several large industrial operators have begun ordering hydrogen vehicles, noting their advantages.

The shipping and aviation industries will need hydrogen power to decarbonise

The size, weight, and range issues associated with batteries become greater still when considering how to sustainably power the shipping and aviation industries. While battery-powered planes and ships are in operation, [81] [82] current technology only permits journeys of modest distances, and with minimal cargo. The use of hydrogen in the form of fuel cells, synthetic fuels, or ammonia, although only nascent technologies, has greater potential to de-carbonise the long-haul freight task carried out by shipping and aviation, and will be key to decarbonising this sector.[83]

5.4: Mixing with Gas and Heating

Hydrogen enrichment is one of the applications of hydrogen which is most ready to adopt, and has featured prominently in the hydrogen strategies of Australian governments as a result. While this does offer a short-term decarbonisation opportunity, there are a number

[76] Bruce, S. et al. (2018), *National Hydrogen Roadmap*, CSIRO, p. 39
[77] Spence, A. (2021), *Electric bus company gears up for zero-emission growth*, The Lead South Australia
[78] ARENA (2021), *New electric buses roll out on Sydney streets*, ARENAWIRE
[79] EVC and ATA (2022), *Electric trucks: Keeping shelves stocked in a net zero world*
[80] Grundler, M. and Kammel, A. (2021), *Why the future of trucks is electric*, Traton
[81] AIRBUS, *Electric flight*, https://www.airbus.com/en/innovation/zero-emission/electric-flight
[82] Yara, *Yara Birkeland*, https://www.yara.com/news-and-media/press-kits/yara-birkeland-press-kit/
[83] IEA (2021), *Global Hydrogen Review*, IEA, p. 101

of efficiency issues which mean that hydrogen enrichment is a suboptimal long-term solution, and should therefore not be used to prolong the operation of gas networks.

Hydrogen is incompatible with current gas appliances and network infrastructure

In residential settings, the appliances which are connected to the gas network, such as stovetops, heaters, and boilers, are all designed to suit the energy content of natural gas. This means they can only operate with a maximum 20% hydrogen mix without being upgraded.[84] A large-scale household gas appliance retrofit to accommodate a higher hydrogen mix would be costly, but not impossible – the conversion of over 40 million appliances from 'town gas' to natural gas took place in the UK over the course of the 1970s.[85] Higher levels of hydrogen content in household appliances would also present significant safety risks – it has been estimated that household explosions would be over four times more likely if methane was replaced with pure hydrogen.[86]

In industrial settings, the lack of any standardisation in gas appliances means that any switch to hydrogen, while possible, could not be coordinated at a large scale as in the household case. Conversion of appliances would be 'site specific and ad hoc', and at the discretion of operators.[87]

The use of hydrogen in the gas network also presents problems for gas network infrastructure. The hard steel that is currently used in gas pipelines is susceptible to embrittlement from exposure to hydrogen.[88] Upgrading pipelines to a more suitable material (polyethylene) is expensive, although the CSIRO has suggested that these upgrades are likely to take place in Australia irrespective of a transition to hydrogen.[89] Hydrogen also has a higher leakage rate than methane, meaning additional 'leak detection and flow control systems' would be required.[90]

Displacing gas with hydrogen is inefficient compared to alternatives

While the above practical hurdles associated with hydrogen gas enrichment are inconvenient but ultimately solvable, more fundamental issues arise when considering the efficiency of using hydrogen in the gas network. For a given volume, the energy content of hydrogen when used for heating is three times lower than that of methane.[91] This means that for a 20%

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[84] Bruce, S. et al. (2018), *National Hydrogen Roadmap*, CSIRO, p. 46
[85] Sansom et al. (2019), *Transitioning to hydrogen*, IET, p. 7
[86] Department for Business, Energy, and Industrial Strategy*, Work Package 7 Safety Assessment: Conclusions Report*, UK Government, pp. 85-86
[87] Bruce, S. et al. (2018), *National Hydrogen Roadmap*, CSIRO, p. 47
[88] H21, *Leeds City Gate* (2016)*,* p. 12
[89] Bruce, S. et al. (2018), *National Hydrogen Roadmap*, CSIRO, p. 33
[90] IEA (2021), *Global Hydrogen Review*, IEA, p. 148
[91] Mansilla, C. et al. in Azzaro-Pantel, C. (Eds.) (2018), *Hydrogen Supply Chains*, Elsevier Academic Press, p. 281

hydrogen mix, only 7% of the total energy delivered would be hydrogen-based, and therefore carbon emissions would only be reduced by 7% (assuming that the hydrogen used is completely emissions-free).[92] This also means that a greater volume of hydrogen will be required to perform the same heating task, and with customers paying for gas on a volumetric basis, their bills would increase by 13%.

Factoring in the production of the hydrogen itself raises further concerns for energy and emissions efficiency. If the hydrogen that is mixed in with natural gas is blue, it has been estimated that, unless the energy used in the blue hydrogen production process is renewable, 'the greenhouse gas footprint of blue hydrogen is more than 20% greater than burning natural gas or coal for heat'.[93] This is largely due to the fugitive methane emissions that occur in the blue hydrogen production process. We note that the estimate here has been subject to criticism, but predominantly from sources that assume rates of carbon capture which are yet to be demonstrated.[94] [95]

If the hydrogen in the gas network is green, rather than blue, then the direct electrification alternative (electric heat pumps) is more energy efficient. The IEA notes that 'PV-powered heat pumps require 5-6 times less electricity than a boiler running on electrolytic hydrogen to provide the same amount of heating'.[96] A concern with the potential large-scale use of electric heat pumps is the cost of reinforcing the electricity network.[97] It is true that a significant amount of renewable generation and storage would be required to service total heating demand through electric pumps. However, as noted above, even more would be needed to produce the amount of green hydrogen necessary to meet the same task.

Despite the relative inefficiency of hydrogen enrichment, section three highlighted that four out of the seven operational green hydrogen projects in Australia are used to this end. All four of these projects, however, are operated by gas companies. Where gas companies can continue to utilise much of their current capital, network infrastructure, and technical expertise with the integration of hydrogen into the gas mix, electrification alternatives provide them with very little commercial opportunity. Therefore, the existence of these projects is not evidence that hydrogen enrichment is an optimal solution to decarbonising the gas sector – it merely demonstrates attempts by gas companies to (understandably) decarbonise their operations in a way which ensures their commercial sustainability.

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92 IEA (2021), *Global Hydrogen Review*, IEA, p. 88
93 Howarth, R. W. and Jacobson, M. Z. (2021), *How green is blue hydrogen?*, Energy Science and Engineering, 9(10), p. 1676
94 Gardarsdottir, S. (2021), *Assumptions Matter When Assessing Blue & Green Hydrogen*, SINTEF blog, https://blog.sintef.com/sintefenergy/assumptions-matter-when-assessing-blue-green-hydrogen/
95 Romano, M. (2021), *Misleading paper on blue hydrogen revised, with modified conclusions*, LinkedIn, https://www.linkedin.com/pulse/misleading-paper-blue-hydrogen-revised-modified-matteo-romano/
96 IEA (2021), *Global Hydrogen Review*, IEA, p. 87
97 Bruce, S. et al. (2018), *National Hydrogen Roadmap*, CSIRO, p. 49

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