THE ANZ

HYDROGEN HANDBOOK

VOLUME II

2024

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FOREWORD

Governments around the world are kick-starting the low carbon hydrogen industry through a range of initiatives including the Inflation Reduction Act in the United States, the European Union's Green Deal, Japan's draft price gap support mechanism and Australia's Hydrogen Headstart program. While still a nascent industry, scale hydrogen projects are now under construction and these developments demonstrate momentum and potential.

In this second edition of the *ANZ Hydrogen Handbook* we provide an update on the global market for hydrogen and its adoption as both an energy source and feedstock into industrial processes.

While hydrogen won't be the decarbonisation solution for every sector of the economy, it could have a key role in decarbonising transportation and heavy industry as well as the power generation sector in certain jurisdictions. Challenges remain however in making renewable hydrogen a cost-effective solution for decarbonising hard-to-abate sectors.

It will take time, commitment and collaboration across industry and governments to realise hydrogen's potential as an alternative, low-carbon fuel source.

The financial services sector will have an important role in the developing global hydrogen market. Investors, banks and export credit agencies will provide the capital for the trillions of dollars needed to fund the global recalibration towards net-zero. We know that through our lending decisions, ANZ is in a unique position to support customers in their transition and finance projects that reduce emissions as well as support economic growth.

We first launched the *ANZ Hydrogen Handbook* in 2022 because we saw a growing need to give readers up-to-date, insightful and practical information on the emerging hydrogen economy. That purpose remains as we update and publish the second edition.

We trust this handbook will continue to be a useful resource for understanding hydrogen and the opportunities it could provide businesses in the transition to net-zero emissions.

Christina Tonkin
ANZ Managing Director, Corporate Finance

VALUE OF HYDROGEN

THE TRANSFORMATIVE POTENTIAL OF HYDROGEN ENERGY IN AUSTRALIA

CURRENT ENERGY ENVIRONMENT

The global shift to a net-zero world requires a significant change in how we generate and use energy. The Australian government has set a target through the Climate Change Act 2022[1] of reducing greenhouse gas emissions by 43% below 2005 levels by 2030[2] and net zero emissions by 2050. Thus, policymakers are eager to decarbonise the energy sector by introducing a wide range of policy and financial incentives to promote the adoption of wind and solar technologies.

While these initiatives provide optimism for reducing emissions, they simultaneously pose challenges to existing energy systems. The intermittency resulting from daily and seasonal variations in sunlight and wind availability can impact the stability of power grids. Moreover, the growing electric vehicle market and the increased power demands for charging can be expected to further strain the grid.

A further challenge to reaching targets is the recent projections that current renewable energy will not be sufficient to make Australia net zero by 2050[3]. Net-zero targets will force Australia to address sectors whose emissions are difficult to abate or can't be electrified. Hydrogen can play a key role in the last mile to net zero by potentially helping in decarbonising sectors such as power generation, heavy transportation, and manufacturing, where electrification is challenging to enforce or simply unfeasible.[4] Although the exact role of hydrogen as a decarbonisation solution is yet to be determined, promoting the inclusion of low emissions hydrogen in the energy mix is crucial for reaching zero-emissions targets.

While many of the current challenges relating to hydrogen include its costs and transportation limitations, hydrogen projects continue to progress globally. The NEOM Green Hydrogen Company (a joint venture between ACWA Power, Air Products and NEOM) announced the NEOM Green Hydrogen project in Saudi Arabia.[5] The project will be the world's largest utility-based hydrogen facility powered entirely by renewable energy. The project is on track to be completed by 2026, where it aims to produce 600 tonnes of green hydrogen per day.[6]

Many countries in east Asia suffer from scarcity of space, lacking in sufficient land masses to build future infrastructures or renewable energy plants.[7] Conversely, Australia has the resources and space to create a hydrogen industry that can both support domestic and international demand. Australia's natural advantages place it in a unique position with access to resources to export hydrogen to trading partners/countries who can't generate their own but are firmly committed to decarbonising.[8]

WHAT IS HYDROGEN?

Hydrogen (H_2) is the chemical element with the symbol and atomic number 1. Hydrogen is the lightest element in the periodic table and the most abundant chemical substance in the universe. At standard temperature and pressure, hydrogen is a colourless, odourless, tasteless, nontoxic, non- metallic, highly combustible gas.

Hydrogen is similar to natural gas in terms of its applications and handling, and from an energy perspective has two outstanding properties:

- Hydrogen is unique among liquid and gaseous fuels in that it emits absolutely no carbon dioxide (CO_2) emissions when the energy is released as heat through combustion, or as electricity using a fuel cell. In both cases the only other input needed is oxygen, and the only by-product is water.
- It is an excellent carrier of energy, with each kilogram of hydrogen containing about 2.4 times as much energy as natural gas.[9]

HYDROGEN IS BEING SEEN AS A CRITICAL COMPONENT OF AUSTRALIA'S ENERGY TRANSITION.

VALUES OF HYDROGEN

Hydrogen possesses the potential to fulfill a crucial role in addressing the energy storage demands necessary for reducing CO_2 emissions, particularly green hydrogen for Australia. As the most abundant element in the universe, its efficacy as a reliable energy carrier has been recognised for many years. Historically, hydrogen technologies have fallen short in delivering innovations that were financially feasible. Nonetheless, developers have persisted in addressing these shortcomings, resulting in significant technological advancements.[10] At present, technologies for producing, storing, transporting, and utilising hydrogen have progressed to a stage where hydrogen is emerging as a viable option for various applications.

Hydrogen is being seen as a critical component of Australia's energy transition. This is due to the values it can bring to the renewable energy landscape. Some of these values include:

1. Zero emissions

Hydrogen serves as a clean and versatile energy carrier. When burned to produce heat or converted to electricity in a fuel cell, it has the unique characteristic of only producing water vapour as a biproduct with no carbon emissions. If hydrogen is produced through the process of electrolysis (the use of electricity to split water molecules into hydrogen and oxygen) which is powered by renewable energies such as solar and wind, it is called Green Hydrogen as the process emits zero emissions.

Green hydrogen can significantly reduce CO_2 emissions far beyond the electricity sector. This is why it can potentially play a key role in decarbonising industries by making them less reliant on fossil fuels.

2. Versatile

Clean and low-emission hydrogen has emerged as an important tool for decarbonising sectors which have historically been hard to abate.[11] These sectors, encompassing aviation, shipping, long-distance trucking, and concrete and steel manufacturing, pose a challenge for decarbonisation due to their reliance on high energy density fuel or intense heat.[12] Hydrogen emerges as a viable solution to address these specific needs. It can help industries that find it challenging to decarbonise based on solar and wind renewable energies alone.

Hydrogen energy is versatile and can be used in various sectors including the energy industry, grid firming, chemicals, and metals production. Hydrogen can be transformed into electricity or synthetic gas and used for commercial, industrial or mobility purposes, such as hydrogen fuel cells for vehicles or an alternative chemical feedstock for industries such as aluminium, cement and steel.[13] Hydrogen can also be used for processing heat in industry but also as a feedstock for ammonia or for calcination in aluminium production[14]; while also being used to heat buildings and homes.

Furthermore, hydrogen can add flexibility to the power industry by enabling seasonal grid storage and balancing growing renewable energy generation shares.[15] By utilising hydrogen, there will be a reduced reliance on traditional fossil fuels, contributing to energy security and promoting diversification.

3. Energy storage

Despite the swift growth in adoption of renewable energy, its progress has been impeded by intermittency issues caused by environmental, seasonal, and daily cycles that can significantly limit their use or efficiency.[16] To complete the final stretch of decarbonisation, these renewable sources require a reliable and firm source for periods when the sun isn't shining, and the wind isn't blowing.

Hydrogen is a valuable energy storage medium that has the potential for large-scale energy storage. Hydrogen can allow excess energy from intermittent renewable sources to be stored for later use, offering a potential solution to the current renewable energy storage challenges. Hydrogen can be stored for a long period of time and can travel long distances, which allows it to be used subsequently for other purposes and stockpiled for future uses.[17] Hydrogen has the flexibility to be stored in tanks as a gas under high pressure or as a liquid at very cold temperatures. However, for cost-effectiveness and safety in large-scale storage, the most economical option is underground in salt caverns, saline aquifers, depleted gas fields or engineered hard-rock caverns.[18] Additionally, hydrogen can also be transported, aiding in balancing the intermittent renewable energy sources.

As such, hydrogen can diversify the energy mix, reducing reliance on fossil fuels and enhancing energy security.

4. Export opportunity

Australia has long been involved in hydrogen development. Its approach is guided by the National Hydrogen Strategy published in November 2019[19], which outlines actions for the country to become a major player in global hydrogen production and trade by 2030. The International Energy Agency (IEA) further forecasts Australia will become the second largest net-exporter of low-emissions hydrogen by 2050.[20]

Australia has plenty of land capacity and access to natural wind and solar power resources. Australia's proximity to major growth markets in big energy importing nations such as Singapore, Japan and Korea will help position Australia to be a superpower of Hydrogen. The export of hydrogen adds value by helping to generate income, diversify export structures and support the decarbonisation of importing countries. Hydrogen stands as a crucial factor in expediting the expansion of clean and renewable energy, holding significant potential in this transformation.

5. Firm source of renewable energy

Renewables such as wind and solar face intermittency and storage challenges.[21] Their main disadvantage is unpredictability due to their reliance on intermittent sources of energy, which makes maintaining a stable supply of electricity complex.

Battery Energy Storage Systems (BESS) and pumped hydro are currently the leading zero emissions technologies being utilised for firming and managing frequency in the National Energy Market (NEM).[22] However, hydrogen also has the potential to aid in smoothing out the variations in renewable supply. Hydrogen can help support grid stability by providing power during peak demand periods where other renewable sources are insufficient.[23]

Hydrogen's ability to provide continuous power generation and serve as a reliable energy storage medium can complement the intermittency of renewables.

6. Job Creation

Hydrogen has become an integral part of the plan to attaining Australia's carbon neutral goals. The 2019 National Hydrogen Strategy[24] was reviewed in 2023 and sets a vision for Australia to develop a Hydrogen industry and become a global superpower for hydrogen production and trade by 2050. The development and implementation of hydrogen technologies can stimulate economic growth and create employment opportunities in the renewable energy sector. From production to infrastructure development, the hydrogen industry can create long-term jobs through new career pathways and establishing a highly skilled workforce.[25]

BANKABILITY

Hydrogen production projects have large upfront capital expenditure requirements for development and construction, followed by long asset lives with relatively low ongoing maintenance capital expenditure requirements. Based on these characteristics, project financing is expected to be a suitable approach to sourcing the capital required to facilitate development, construction and operation of these projects. While some hydrogen projects will be financed via the relevant sponsor's corporate debt facilities, project financing is expected to be an attractive alternative, as it is for projects with similar characteristics in the infrastructure, energy and mining sectors.

PROJECT FINANCING IS EXPECTED TO BE AN ATTRACTIVE ALTERNATIVE, AS IT IS FOR PROJECTS WITH SIMILAR CHARACTERISTICS IN THE INFRASTRUCTURE, ENERGY AND MINING SECTORS.

Project finance is the financing of long-term infrastructure, industrial projects, and public services using a non-recourse financial structure. The debt and equity used to finance the project is repaid solely from the cash flow generated by the project. The project assets are owned by a Special Purpose Vehicle (SPV). The SPV is the Borrower and lenders only have recourse to the SPV, the project assets and the cash flows they generate. For many project sponsors, project finance is an efficient means of securing capital because the debt is supported solely by project cash flows, as opposed to leveraging the sponsor's balance sheet.

For project financing to be viable, the project's commercial structure must be structured in a manner that enables the project to generate stable and predictable cash flows that can be forecast over the project life with a reasonable level of confidence. The following attributes would enable a project to achieve this:

- Contracted Offtake: Long-term offtake agreements with reputable investment grade counterparties that have the capabilities to fulfil their obligations. Price and volume terms that sufficiently minimise uncertainty in relation to forecast project cash flows.
- Contracted Feedstock Supply: Long-term feedstock (renewable electricity and water) supply agreements with capable and creditworthy counterparties. Price and volume terms that eliminate gap risk (with respect to offtake terms) and minimise uncertainty in relation to forecast project cash flows.
- Operations and Maintenance: Long-term, fixed price (to the extent possible) Operations and Maintenance Agreement with a reputable, experienced, creditworthy and highly capable operator.
- New Technology Risk Protections: Sufficient contractual mitigants in relation to project components that are not commercially proven at scale. For example, a long-term performance warranty from a reputable, experienced and creditworthy electrolyser OEM.
- Construction Contracting Arrangement: Well considered construction contracting arrangement, with responsibilities / risks allocated to creditworthy contractors that have the required experience, capability and capacity to manage them. Fixed price, date certain EPC contracts with appropriate delay and performance protections.
- Simplicity: Unnecessary complexity could limit the volume of liquidity available for financing. Noting many proposed hydrogen projects will require multibillion dollar financings, maximising available liquidity will be critical to ensure successful execution.

In addition to the attributes listed above, the following attributes relating to a project's location are likely to determine its attractiveness to financiers:

- Well Considered Location: The project's location has been optimised when taking into account:
  - Proximity and access to high quality renewable energy resources;
  - Proximity and access to water supply of sufficient volume and quality;
  - Required enabling infrastructure (including electricity transmission and water pipeline) is in place or will reach completion well before it is required;
  - Required transport and logistics infrastructure; and
  - Proximity to hydrogen and ammonia buyers, domestic and/or export.

- **Stable and Predictable Legal and Regulatory Environment**: A quality of many jurisdictions globally, including Australia and New Zealand.
- **Favourable and Supportive Government Policy Environment**: This is a benefit for projects in Australia, where there are a multitude of federal and state government policies aimed at developing a globally competitive hydrogen industry.
- **Availability of Skilled Labour**: Local workforce has the required technical expertise to facilitate the successful construction and operation of a project of this nature.

Many of the proposed hydrogen projects will require multibillion dollar debt financings, requiring liquidity that is beyond what the commercial bank market will be able to provide alone. As with previous financings of mega projects, Export Credit Agencies (ECAs) will be a critical source of liquidity for debt financing. ECAs are sovereign backed institutions that can share risks with commercial banks either by guaranteeing or lending alongside bank loans. In Australia, ECAs have helped finance LNG, iron ore and wind projects. ECAs can support projects where overseas companies are to supply goods or services into construction or operation. Certain ECAs can support projects where there is equity investment from its home country and/or offtake from the project to its home country. In addition, Australia's ECA, Export Finance Australia, can support projects that intend to export in the future.

HYDROGEN 101

HYDROGEN 101

HOW IS IT PRODUCED?

An obstacle to realising hydrogen's clean energy potential is that it is virtually non-existent in its free form on Earth. Energy must be used to liberate it from the material forms in which it exists, such as in fossil fuels, water, biomass, minerals and naturally occurring underground deposits. The most common production methods include thermochemical reactions (utilising steam-methane reforming, gasification or pyrolysis processes with fossil fuels) or through electrolysis. With the application of carbon capture, utilisation and storage (CCS/CCUS), both of these methods can produce clean hydrogen to help decarbonise energy systems and industrial processes. There are a range of other hydrogen production methods which are explored further within this report, each resulting in different levels of carbon emissions, and they are classified under colourful names.

Green Hydrogen

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

The reaction occurs in a device known as an electrolyser. Two types of electrolyser systems are used most commonly commercially, being Alkaline and PEM technologies.

Hydrogen production via electrolysis requires high- purity water. Most commercial electrolysers have an integrated deioniser to purify the water. For every 1 kg of hydrogen produced, a minimum of approximately 9 kgs of water is required.[26] To get a sense of the amount of water required for large-scale hydrogen production, consider the challenge of producing enough hydrogen to match the energy content of Australia's LNG production. The energy content is equivalent to about 38 million tonnes of hydrogen, which would require 311 gigalitres of water to be electrolysed. This is a large volume of water but is comparatively a small proportion of Australia's current annual water consumption.

A third type of technology known as solid oxide electrolysis has solid oxide electrolysis cells with high efficiencies, but also operate at much higher temperatures than alkaline or PEM electrolysis, therefore requiring an external heat source.[27]

Blue Hydrogen

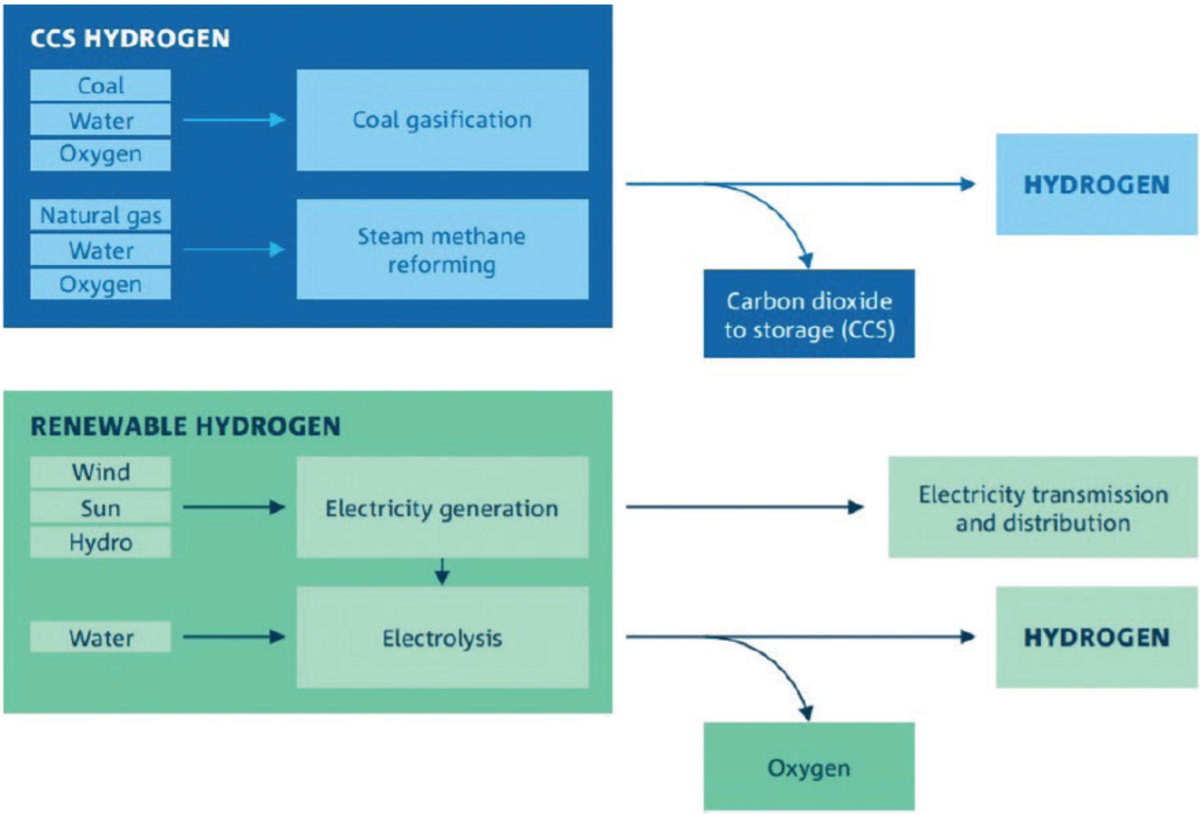
In fossil fuel-based thermochemical processes used to produce hydrogen, energy from fossil fuels drive chemical reactions that lead to extraction of hydrogen. In almost all cases CO_2 is a by-product. When the CO_2 is captured via CCS, it is considered blue hydrogen.

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

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

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

Hydrogen production pathways considered in this report.



Source: Green and blue hydrogen (chiefscientist.gov.au).

TRANSPORTING AND STORING HYDROGEN

Hydrogen is a very light gas and requires conversion for storage and transport due to its low density. This can be achieved in predominantly three ways:

1. Compression
2. Liquefaction
3. Chemical compounding
   - With other molecules to form liquid organic hydrogen carriers (LOHCs)
   - With nitrogen to form ammonia (NH_3)
   - With CO_2 to form methane or methanol

Hydrogen liquefaction, for example, involves cooling via processes similar to those used in the LNG industry, albeit these are significantly more energy intensive given the lower temperature (–253°C) required.

Another attractive storage and distribution approach is to inject pressurised hydrogen into natural gas pipelines, which can utilise existing infrastructure.

Pipelines are predominantly made of steel and operate at pressures >1 MPa. Their ability to transport 100% hydrogen will depend on their susceptibility to the embrittlement caused by hydrogen in some metals. The previous view was that up to circa 15% hydrogen can be used in existing pipeline networks.[28] The Hydrogen Project South Australia (Hyp SA) project began operations in 2021 in South Australia and introduced up to 5% hydrogen in existing pipelines to monitor the impact on infrastructure and household appliances.[29] In 2023, the Hyp SA was able to successfully deliver 5% blended renewable hydrogen to nearly 4,000 additional residential and commercial properties.[30] Risk factors include the condition of the pipe and welds, grade of steel, thickness, types of welds and operating pressure. Recently, APA's 2023 laboratory study concluded that up to 100% of pure hydrogen can feasibly be transported through their existing pipelines.[31] The study successfully transmitted hydrogen through West Australia's Parmelia gas pipeline over a 43km section of the pipeline.

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

THE ECONOMICS OF HYDROGEN PRODUCTION

Currently, fossil fuel-based processes produce hydrogen at a lower cost than renewable electricity electrolysis technologies. While recent volatility in gas prices from various geopolitical events has impacted prices, Bloomberg conveys that hydrogen from natural gas without CCS costs in the range of US$0.98-2.93/kg (A$1.50-4.37/kg) hydrogen. Grey hydrogen is the cheapest form at present as blue hydrogen (with CCS) costs US$1.80-4.70/kg (A$2.69-7.03/kg) hydrogen.[32] Green hydrogen remains the most expensive form as its costs vary greatly from US$4.5-$12/kg of hydrogen. Costs across all forms are expected to decrease in line with research and development of technologies. The production cost of hydrogen from natural gas is influenced by various technical and economic factors, with the most important factors being gas prices and capital expenditure. Costs for coal gasification are similar to those for natural gas steam reformation, where project viability is mostly dependent on the size of capital expenditure requirement, coal availability and coal prices.

At present, blue hydrogen is a more cost-effective way of producing hydrogen without large emissions and this is a route some nations are taking. However, Australia is pursuing green (or renewable) hydrogen as it seeks to replace and reduce fossil fuels. Renewable electricity electrolysis technologies currently produce hydrogen at a higher cost and does so with inherently low emissions. While electrolysis technology is still relatively immature, ongoing innovation is developing the industry Unpredictability across electricity prices and supply chains impacts hydrogen costs, however, green hydrogen costs are likely to decrease over time as a number of influential factors around it decrease.[33] Australia is targeting hydrogen production at less than A$2/kg[34] which the Australian Government announced in 2020, calling it the 'H_2 under 2' strategy.

BUILDING AT SCALE WILL BE KEY TO BRINGING HYDROGEN SUPPLY COSTS DOWN.

Building at scale will be key to bringing hydrogen supply costs down. In particular, minimising large- scale transport and storage costs will be critical to ensure that Australia's competitive advantage from its abundant natural resources is not offset by its distance from potential markets.[35]

Ultimately hydrogen must be cost competitive with other fuels in specific application areas if it is to achieve widespread adoption. For example, hydrogen would achieve competitiveness at A$2/kg with the landed costs of natural gas in importing countries.[36]

WHAT IS THE MARKET FOR HYDROGEN?

The worldwide demand for hydrogen is increasing as imported hydrogen is becoming central to multiple nations' economies. Production costs are falling, technologies are progressing and the push for non-nuclear, low- emissions fuels is building momentum. Australia is well-positioned to benefit from the growth of hydrogen industries and markets.

Hydrogen's versatility means it can play a key role across all energy sub-sectors. It can be used as an exportable zero- emissions fuel. It can be burned to provide heat for buildings, water and industrial processes. It can power transport through fuel cells, being particularly suitable for long-haul heavy transport. It can help make the entire energy system more resilient by providing a flexible load, frequency control services and dispatchable electricity generation. It can also be converted into a number of other products such as methanol which has a range of different uses from clothing to fuel and ammonia for fertilisers.

The most immediate economic opportunities for Australia are to establish itself as hydrogen supplier of choice to other nations that are hungry for hydrogen as a cost- effective route to reducing emissions, while also decarbonising our own industries domestically.

Due to its potential for decarbonising energy systems, many countries around the world are investing to develop hydrogen energy value chains. For example, Japan and South Korea which depend heavily on imported fossil fuel energy, are seeking to replace those fuels with imported hydrogen. Their emerging import demand equates to a large export opportunity for Australia.

Australia has an abundance of low-cost renewable solar and wind energy, and an abundance of low- cost brown coal alongside CCS sites. Coupled with existing expertise in natural gas infrastructure and shipping, Australia is well- positioned to take a lead in the emerging hydrogen export market.

Export of hydrogen represents a key opportunity for Australia. Demand for hydrogen exported from Australia is estimated to be at more than three million tonnes per year by 2040, which could be worth up to US$10 billion per year to the economy.[37]

COLOURS OF HYDROGEN

COLOURS OF HYDROGEN

Hydrogen is the lightest and most abundant chemical substance in the universe, however it rarely appears in its free form on Earth so requires energy to separate it from other compounds. The different methods of producing it have colourful names.

Main types of Hydrogen Energy		
	Green	Produced through electrolysis of water using a renewable power source. Zero carbon emissions in production and combustion.
	Blue	Produced from fossil fuels, including natural gas or coal. Similar to the process for grey or brown hydrogen, except carbon emissions are captured and permanently sequestered.
	Grey	Produced from methane or natural gas through steam methane reforming with material carbon emissions released during production.
	Brown	Produced from coal through gasification with material carbon emissions released during production. Also known as **black hydrogen**.

Other types of Hydrogen Energy		
	Turquoise	Produced when natural gas is broken down with the help of methane pyrolysis (as opposed to steam methane reforming). The process is driven by heat produced with electricity, rather than through the combustion of fossil fuels. The output of carbon in solid form (rather than CO_2) means there is no requirement for CCS. Where the electricity driving the pyrolysis is renewable, the process is zero-carbon or even carbon negative if the feedstock is bio-methane rather than fossil methane (natural gas).
	Pink/ Purple/ Red	Produced by electrolysis using nuclear power.
	Yellow	Produced by electrolysis using solar grid electricity.
	White/ Gold	A naturally-occurring geological hydrogen found in underground deposits and created through fracking. Several reservoirs have been found across the world, however there are no developed strategies to exploit this hydrogen at present.

GREEN HYDROGEN

As a low carbon option, the debate is narrowed to green and blue hydrogen, especially in Australia as there is no nuclear industry (which can also be included as a low carbon option for producing hydrogen in other countries).

THE PRODUCTION OF HYDROGEN WITHOUT THE GENERATION OF CARBON EMISSIONS.

Green hydrogen is the production of hydrogen without the generation of carbon emissions. Production occurs through a process of electrolysis, which uses an electrical current to separate the hydrogen from the oxygen in water. When the electrical current is powered through renewable energy such as wind or solar, the energy is produced without emitting carbon dioxide making it clean or sustainable.

Electrolysis occurs through an electrolyser, which can provide grid flexibility during period of excess renewable electricity load and mitigate curtailment and/or negative power price event. While currently more expensive than any other commercialised form of hydrogen production, electrolyser production costs are expected to fall sharply once at scale.

Most of the production costs are from electricity generation and as the price of renewable power continues to fall, so will the cost of the electricity generation. It also requires significant input of deionised water.

BLUE HYDROGEN

Blue hydrogen is produced using fossil fuels with the CO2 emissions captured and sequestered through a process known as Carbon Capture and Storage (CCS). Blue hydrogen is primarily produced by splitting natural gas into hydrogen and carbon dioxide through either Steam Methane Reforming (SMR) or Auto Thermal Reforming (ATR) with the emissions captured.

Currently, it is more economical than green hydrogen and can produce much larger volumes of low carbon hydrogen. However, blue hydrogen is at a premium over grey and can be exposure to price dynamics in the gas market (including geopolitical events).

While blue hydrogen is a viable option for some other nations, for Australia, the priority for Australia is green hydrogen. Blue hydrogen can be costly and while more environmentally friendly than brown and grey hydrogen, it does not remove the issue that the carbon will continue to exist, albeit not being released into the air and can be stored in existing infrastructure.

GREY AND BROWN HYDROGEN

Grey hydrogen is extracted from natural gas or methane using steam reforming, while brown or black hydrogen are produced via gasification where carbonous materials are heated into a gas. Both release carbon emissions into the atmosphere with no carbon capture mechanism.

Most hydrogen currently comes from natural gas, but this process also creates a lot of carbon waste. Natural gas contains large amounts of hydrocarbons – hydrogen chemically bonded with carbon. Catalysts can break these bonds, but the excess carbon then creates CO_2.[38]

Despite the use of a valuable resource, Special Advisor Hydrogen at International Energy Agency (IEA) - Noé van Hulst said that while grey hydrogen is currently the cheapest, "too often people assume that the price of grey hydrogen will remain at this relatively low level for the foreseeable future"[39]. He believes "that ignores the IEA's projection of a structural rise in natural gas prices due to market forces. And more importantly, it fails to take into account the potential volatility of gas prices."

CARBON CAPTURE AND STORAGE

Carbon Capture and Storage (CCS) is an integrated suite of technologies that can prevent large quantities of the greenhouse gas carbon dioxide (CO_2) from being released into the atmosphere.

There are three major stages involved in this technology[40]:

1. CAPTURE - the separation of CO_2 from other gases produced at large industrial process facilities such as coal and natural gas power plants, steel mills and cement plants.
2. TRANSPORT - once separated, the CO_2 is compressed and transported, usually via pipelines, to a suitable site for geological storage.
3. STORAGE - CO_2 is injected into deep underground rock formations, often at depths of one kilometre or more. CO_2 can be stored in oil and gas reservoirs, un-mineable coal seams and saline reservoirs.

OTHER CONSIDERATIONS

While the use of colours to distinguish the various sources of hydrogen production is useful, it fails to provide the full picture of carbon intensity and pricing. As the hydrogen industry develops and projects in the pipeline increase, end users are beginning to place emphasis on these factors.

The colour system simplifies the discussion around hydrogen sources, however it does not consider the carbon required to produce the hydrogen from the source or evaluate the carbon costs related to transportation.

From the regulatory perspective, there is also no single international body which governs the colour system and sets benchmarks for the carbon intensity allowed in each category. For example, while green hydrogen may not produce any emissions through production and combustion, the colour system lacks insight into the full value chain (including the high emissions that may come from transporting the hydrogen to end users). In Australia, the Guarantee of Origin scheme will measure the emissions intensity of the source of supply, for example, hydrogen buyers will consider the emissions intensity not the colour of the hydrogen.

The decline in the cost of renewables and increased incentives within the market position hydrogen as a strong option in global decarbonisation, particularly in Australia.

To achieve the full commercialisation of a hydrogen industry, there is still some way to go for hydrogen to reach cost-parity with its fossil fuel competitors. However, given its potential to play a significant role in the energy transition, many companies are already looking at where hydrogen capabilities may play a role within their business, forming early collaborations with key partners and engaging in selective M&A and subsidised pilot project activities.

Several countries are investing in research, development and planning around hydrogen with the emphasis on green hydrogen and blue hydrogen for nations which do not have the abundance of renewable energy sources.

Industry Considerations

- Environmental, social and governance factors impacting the future of hydrogen must also be considered by all those that participate throughout the hydrogen value chain.
- The safety of hydrogen is a common concern even though it is safer to handle and use in comparison to other commonly used fuels. Hydrogen is non-toxic and due to its light density; dissipates quickly when released allowing for rapid dispersal in the case of leaks.
- The use of water as a feedstock for developing molecular hydrogen can also be of concern due to availability and restrictions on the resource. Green hydrogen currently requires the input of high-purity water, however a number of studies are currently underway in order to utilise sufficient supportive infrastructure (e.g. desalination, reverse osmosis plants) to combat the restrictions and strain on Australia's water security. It is important to note that in order to maintain production being 100% green, these processes would also require firm renewable energy to operate, which is highly energy intensive by nature.
- The electricity requirements needed for clean hydrogen to meet global energy demands are vast. The production, storage and transportation of hydrogen itself can be quite energy intensive, however with global renewable electricity capacity expected to increase while costs decline, this is anticipated to support the consumption requirements.
- The use of CCS in the production of blue hydrogen requires investment in highly capital-intensive long-life assets. In addition, while capture technologies are well- developed, limited application in most industries increases perceived risk and regulatory acceptance.
- However, emissions reduction commitments require the adoption of a range of technologies and mitigation solutions and the acceptance of CCS projects are expected to come with scaling over time.
- The demand/customer offtake in comparison to supply availability for hydrogen will be increasingly important given the rapid pace of growth within the industry.
- To achieve an equilibrium between supply and demand of hydrogen, this will require further infrastructure build-out requirements and increased energy affordability.
- And finally, in regard to implications for other industries, hydrogen should be seen as an opportunity for oil and gas producers and infrastructure operators to expand the terminal life of their assets and reduce stranded asset risk. While the ramp up of a green hydrogen economy may take time to build, blue hydrogen is uniquely positioned to act as a bridge to transition the energy system, and help build the momentum required to achieve global decarbonisation in a thriving hydrogen economy.

AUSTRALIA AND HYDROGEN

AUSTRALIA AND HYDROGEN

Global focus on net-zero emissions has put a spotlight on the production of low emission hydrogen and its use in new sectors such as electricity generation and transportation. With its versatility in energy production, direct combustion and as a transport fuel, countries around the world are turning their attention to hydrogen.

Australia is well positioned to produce, use, and export hydrogen – with a clear focus on green hydrogen. Continued investment and development will help to ensure Australia's competitive place in the global hydrogen industry as a thought leader and as an exporter.

A switch to hydrogen for Australia would not only be expected to avoid greenhouse gas emissions equivalent to one third of Australia's fossil fuel emissions by 2050, but also generate an additional A$50 billion of GDP while creating more than 26,000 jobs.[41]

With an estimated 262,000 square kilometres of space available to be used for hydrogen (circa 3% of Australia's land and larger than the average EU member state), stable political system and favourable geography, Australia is in a prime position to utilise hydrogen for energy, transportation, and export.[42]

The hydrogen export industry could reach 382 petajoules (PJ) in 2040 contributing over A$2.5 billion to the economy while employing over 4,000 people.[43] Overall, the hydrogen export industry could create over 16,000 jobs and add over A$10 billion to the economy, through increased spending and employment along the entire supply chain needed for export in mostly regional areas.[44]

1. ENERGY OPPORTUNITY

Hydrogen can play a vital role as the grid transitions towards variable renewable energy, helping to smooth out the system. Excess renewable energy from solar or wind which is not needed by the electricity system can be used to power electrolysers to form green hydrogen. This could see further integration of renewables into the National Electricity Market (NEM) and improve grid responses.

By 2050 it is expected that 15% of the worlds global energy use will be from hydrogen, as countries turn toward low emission or green energy.[45]

2. AUSTRALIA'S HYDROGEN EXPORT POTENTIAL

Australia is expected to service 9.1% of global export demand for hydrogen in 2025.[46] With its available land, renewable energy and stable political system, Australia is a prime candidate in the global hydrogen export industry. Many of Australia's major trading partners are both interested in hydrogen usage but do not have the same characteristics as Australia to produce it, yielding a sizable export opportunity for Australia.

To be able to export hydrogen, investment in infrastructure is necessary. Proposed regional hydrogen hubs all have direct access to deepwater port infrastructure that is currently used for bulk commodity throughput. With minor investments and upgrades, these ports can support the storage and transportation of hydrogen.

As of the 2022 hydrogen strategy report by the Department of Climate Change, Energy, the Environment and Water (DCCEEW), there are 45 projects in Australia which plan to use hydrogen chemical feedstock for both export and domestic markets, and 23 renewable based ammonia production plants in Australia- with several of the larger plants aiming to export.

Hydrogen Hubs (csiro.au)

Australia has seven regional hydrogen hubs which are based in:

1. The Pilbara and Kwinana in Western Australia
2. The Hunter in New South Wales
3. Bell Bay in Tasmania
4. Gladstone in Queensland
5. Port Bonython in South Australia.

AUSTRALIA HAS A COMPETITIVE ADVANTAGE OVER OTHER POTENTIAL HYDROGEN EXPORTING COUNTRIES.

3. WHY AUSTRALIA?

Australia has a competitive advantage over other potential hydrogen exporting countries such as Norway, Qatar and the USA.[47]

Australia's main advantages come from:

- Lower costs of hydrogen production, storage and transportation;
- Pre-existing relationships with trade partners that are likely to have strong demand for hydrogen.

Cost of production

In the 2018 hydrogen roadmap the Commonwealth Scientific and Industrial Research Organisation (CSIRO) forecast the levelized cost of hydrogen (LCOH) for various production technologies. The LCOH represents the net present value of the unit cost of hydrogen over a hydrogen production asset's lifetime (taken as a proxy for breakeven hydrogen price).

From these estimates, proton exchange membrane (PEM) electrolysis is the most suitable production method for export. The capital expenditure necessary for a PEM electrolyser is high, but PEM electrolysers are flexible allowing them to operate with variable renewable energy power supply, helping to minimise the cost of inputs during peak pricing periods. Operators could store excess renewables supply during low demand or price periods by turning it into hydrogen, which could balance out the investment.

Renewables pricing

Fifty-70% of the production cost of hydrogen is the cost of electricity.[48] Australia's relative abundance of renewable energy forms a viable means of hydrogen production power. The continued roll out of renewable energy is key to Australia's green hydrogen future.

Green hydrogen is a key focus for many countries. Under this process, renewable electricity generated from solar, wind or other forms splits water into hydrogen and oxygen in an electrolyser. Renewable energy access is therefore central to green hydrogen production. Renewable energy zones (REZs) will play an important role in green hydrogen production and the broader Australian renewables strategy. REZs are clusters of large-scale renewable energy projects which can be developed using economies of scale.

REZs will be serviced by new transmission network infrastructure, including high-capacity transmission lines, poles, wires, and energy hubs which will transfer power generated by solar and wind farms to electricity users. This infrastructure will be critical for the successful operation of REZs, helping to transport generated and stored power to end users or into hydrogen production.

Storage and transportation

Australia has an abundance of unused liquid natural gas, coal, and oil assets which could be used as hydrogen storage facilities. Hydrogen is usually stored via compression in storage tanks, in salt caverns or by turning hydrogen into ammonia or into a liquid state. Pre-existing storage facilities which were previously used in the oil and gas industry can be leveraged to become hydrogen compatible quickly and without too much investment. Pre-existing infrastructure able to be readily converted to support hydrogen enhances Australia's ability to use and export it.

Hydrogen for domestic use will likely be transported via road or purpose-built pipelines. These are unfeasible for export given Australia's geographic position. For longer distances, shipping remains the most viable, with an estimated cost of between A$0.03 and A$0.61/tkm.[49] All seven regional hydrogen hubs have access to deepwater ports, reducing unnecessary costs nonrelated to shipping. Access to Asia remains feasible with Japan, Korea and China all expected to have increasing demand with little ability or space to produce their own hydrogen.

Other hydrogen vectors (form of transporting hydrogen) such as methanol (CH_3OH, liquid) or ammonia (NH_3, gas) are likely to be used due to their relative stability and cost effectiveness compared to transporting hydrogen in its pure gaseous form.

In April 2022, a world first pilot project to export liquid hydrogen, the Susio Project, successfully exported liquid hydrogen from Victoria to Japan. It was the first of its kind shipping liquefied hydrogen from one continent to another, and required strong collaboration from the consortium including AGL, Marubeni, and Sumitomo. This highlights Australia's prowess at the forefront of hydrogen technology and export.

Trade relationships

Australia has free trade agreements with many countries including Japan, the Republic of Korea, China, and Singapore. The established trade relationships in commodities and energy could be leveraged for hydrogen export, proving a competitive advantage for Australia.

AUSTRALIA'S CURRENT HYDROGEN-RELATED INFRASTRUCTURE

The necessary infrastructure is critical for the production, storage, and transportation of hydrogen. With hydrogen playing an ever-important role in Australia's renewables strategy, there are forecasts for up to A$80 billion of necessary spend by 2030.[50] Although an intensive capital outlay will be required, Australia's current infrastructure could be the backbone to support the industry.

Australia has over 15 hydrogen projects that have passed financial investment decision, with several other commercial stage projects in early phases, showcasing the extensive commitments from both the public and private sector into hydrogen related infrastructure.

Current production of hydrogen is c.650 ktpa in Australia and is produced through Natural Gas Steam Methane Reforming (SMR)[51].

Sixty-five percent of the hydrogen produced in Australia is used in the synthesis of ammonia through reacting it with nitrogen gas,[52] with the rest used in crude oil refining by using hydrogen to remove sulphur from fuels.[53]

1. PRODUCTION

Central to the production of green hydrogen is a stable and secure electricity source and water - both key inputs to the process.

2. AUSTRALIA'S ENERGY

The Australian energy market operator (AEMO) operates two markets and power systems in Australia, the National Energy Market (NEM) and Wholesale Electricity Market (WEM). AEMO has a mandate to ensure security of electricity and systems, the maintenance of electricity and gas markets, and to lead the future of Australia's energy system.

Having a secure, reliable, and affordable supply of electricity is central for renewable hydrogen development. To supplement traditional energy sources, hydrogen production could be fuelled by renewable energy.

The energy transition and renewable energy is central to the strategy of many public and private sector firms. With that, production and distribution of renewable energy is a focus for Australia's private and public sector. In collaboration, Renewable Energy Zones (REZs) have arisen. REZs are clusters of large-scale renewable energy projects which can be developed using economies of scale to feed energy into the grid. It is expected REZs will play an important role in providing clean energy to produce green hydrogen.

Increased production and transmission projects will help to ensure Australia has viable renewable energy and ensure the security, reliability, and affordability of supply to produce green hydrogen.

3. WATER

Hydrogen can be formed through the electrolysis of water. Electrolysis is a complex process which uses an electric current to convert water molecules (H_2O) into hydrogen (H) and oxygen (O_2). The hydrogen is stored in pipelines and can be used for energy while the oxygen can be released into the air.

Australia has robust water supplies, however desalination and purification plants, dams and pipelines may require investment to ensure pure water is available for electrolysis. Given water's relatively cheap price, the infrastructure in securing and processing it remain a barrier to production.

4. GAS NETWORK

More than 100 natural gas transmission pipelines exist across Australia, connecting gas production centres to distribution networks in major demand centres. Significant research and development projects are being undertaken to assess if current gas transmission channels could be adopted for hydrogen transmission and transportation.

Feasibility studies show that gas blends of 5-20% hydrogen are feasible without the need for significant investment on top of current gas infrastructure.[54] A national Gas infrastructure plan, announced by the Australian Government in the 2020 Budget, provides an outlook for the next 20 years of investment, highlights the potential to leverage current infrastructure for hydrogen transportation.

5. LAND TRANSPORTATION

With vast expanses, road, and rail transportation play an important role in connecting Australia internally. Before 2025, it is expected that road and rail transport will be the dominant method of hydrogen transport until pipelines are further developed.[55] Australia has developed a network for domestic transport of hazardous chemicals and liquid natural gas through existing supply chains. These systems and practices can be leveraged for hydrogen, with changes to existing facilities as needed to cater for specific projects and safety and regulatory requirements.

Hydrogen can be compressed to pressures between 200-700 bar and transported via truck which is already used for small scale projects. For longer distances, trucking liquid hydrogen is a more economical means, providing greater trucking capacity reducing the number of trips needed and the associated expense. Either way there is a reliance on Australia's road system for transportation.

6. HYDROGEN STORAGE FACILITIES

After transportation, hydrogen is normally kept in tanks dependent on if it is liquified, compressed, ammonia or Methylcyclohexane (MCL). Technical expertise is readily available from the existing chemical, oil and gas industry to make storage solutions hydrogen compatible.

Longer term solutions are being explored, with possibilities of storing hydrogen in salt caverns, or pre-existing depleted gas fields. Australia currently has seven locations for natural gas storage on the east coast, with two other spots in Western Australia highlighting potential hydrogen storage infrastructure.

7. PORT INFRASTRUCTURE

Australia plans to be a key player in the export of hydrogen into the Asian region and became the first country in the world to export hydrogen when it shipped a liquified form to Japan in 2022.[56] With aspirations to be the dominant East Asian hydrogen exporter, it is estimated the investment spend to reach that level could be up to A$80 billion.[57]

For international transport, shipping remains the only viable means of transportation given price and distance. Multiple Australian ports currently ship ammonia highlighting that Australia already has infrastructure in place to export hydrogen. The National Hydrogen Strategy identified 30 potential ports which could be developed into hydrogen export hubs due to existing and potential infrastructure capacity: providing capacity and capability for electricity, water, gas pipelines and storage.

If hydrogen were to be liquified prior to shipping, liquefication plants and loading facilities should be placed in a close vicinity to minimise any losses in transportation and boil off. Importantly any conversion of hydrogen into other carrier forms other than its natural gaseous state will require additional power infrastructure to be installed to ensure a stable and consistent energy source.

All in all, Australia's current infrastructure could support hydrogen production, however, will require research, development and investment for future scale.

AUSTRALIA'S NATIONAL HYDROGEN STRATEGY

The Federal Government and the Council Of Australian Governments (COAG) Energy Council commissioned the Chief Scientist to develop the blueprint for a national hydrogen strategy. The final National Hydrogen Strategy was released at the November 2019 COAG Energy Council meeting in Perth. In February 2023, the Energy and Climate Change Ministerial Council (ECMC) agreed to review the strategy.[58]

The National Hydrogen Strategy aims to position Australia's hydrogen industry as a major global player by 2030. Notably, individual states also have hydrogen strategies or programs in place. Australia is endeavouring to find ways to approach hydrogen in a 'clean' way with many of the funding mechanisms supporting green technologies and production.

While Australia prioritises hydrogen and was an early adopter in providing a published government document, other countries are in development of or have published strategies for hydrogen. There was a significant uptick from 2020 particularly in European countries around the time when the European Commission published a strategy paper. Countries in the table below have published documentation, strategies and / or roadmaps in relation to Hydrogen (either with involvement or commissioned by respective government, at October 2023).[59] This table is not an exhaustive list.

Countries Adopting a Hydrogen Strategy

2019	2020	2021	2022	2023
Australia	Canada	Belgium	China	Algeria
Austria	Chile	Colombia	Croatia	India
Japan	EU Commission	Czech Republic	Greece	Ireland
New Zealand	Finland	Hungary	Namibia	Malaysia
Norway	France	Luxembourg	Oman	Türkiye
South Korea	Germany	Morocco	Singapore	United States
	Italy	Paraguay	South Africa	
	Netherlands	Poland	Switzerland	
	Portugal	Russia	Uruguay	
	Spain	Slovakia		
		Sweden		
		Ukraine		
		United Arab Emirates		
		United Kingdom		
		United States		

Source: CSIRO- HyResource

WHAT IS AUSTRALIA DOING NOW?

Australia's National Hydrogen Strategy[60], as published in 2019, has several key pillars to guide its focus. The strategy outlines the aim to reduce entry to market barriers, create supply and demand within the market and be globally market competitive from a cost perspective. The policy outlines that to achieve these goals, the Australian Government will work with states to support and develop the Australian (particularly clean) hydrogen industry and aim for unity in the regulatory and approval processes across the nation. The Australian Government also outlined their intentions to support partnerships while prioritising the safety and environmental benefits for Australia.

Australia has demonstrated the importance of the hydrogen industry, in Australia, as the DCCEEW released 'State of Hydrogen 2021' and 'State of Hydrogen 2022' in 2022 and 2023 respectively. Regarding Australia's National Hydrogen Strategy, the Energy and Climate Change Ministerial Council (ECMC)'s review of the 2019 document remains in line with the initial pledge to be a hydrogen world leader by 2030 as other countries gain momentum in releasing their own strategies and domestic agendas. The ECMC highlight up to A$300[61] billion of potential hydrogen investments as well as Australia being home to the largest project pipeline in the world as key opportunities the strategy will be developed around. The Australian Government is the lead in the review, with support from the States and Territories.

THE HYDROGEN HEADSTART PROGRAM AND GUARANTEE OF ORIGIN SCHEME ARE TWO KEY PILLARS OF THE STRATEGY.

Australia has several key programs to support industry development. The **Hydrogen Headstart Program** and **Guarantee of Origin Scheme** are two key pillars of the strategy. Additionally, hydrogen is a component of the Rewiring the Nation program which the Australian Government is investing A$20 billion in upgrading and transforming the electricity grid.[62]The Australian Government is also implementing the Safeguard Mechanism which aims to reduce emissions of top industrial emitters. It aims to do this by implementing a baseline which continues to reduce over time.

HYDROGEN HEADSTART PROGRAM

In the 2023- 2024 Federal budget, the Australian Government pledged A$2 billion for a Hydrogen Headstart Program. This is being administered and designed by the Australian Renewable Energy Agency (ARENA) and DCCEEW.[63] They have worked to design the program in conjunction with other stakeholders including the CEFC (Clean Energy Finance Corporation). The purpose of this program is to help accelerate the development of Australia's hydrogen industry with emphasis on large scale green hydrogen projects.

In addition to the A$2 billion, there will be funding of A$2 million over two years to support First Nations communities in engaging with developers of relevant projects.[64]

Successful candidates will receive funding as a production credit, the purpose of this is to bridge the gap between the cost of hydrogen produced from renewables and its market price.

The program will be implemented by ARENA who will select large Australian-based projects that produce hydrogen from renewables (or from derivative products made from hydrogen, including ammonia).

Expressions of interest were opened in October 2023, with project selection due to be completed by the end of 2024.

Shortlisted candidates were announced in December 2023 and are listed in the table.[65]

Applicant	Project	Electrolyser Size (MW)	State	End Use
bp Low Carbon Australia Pty Ltd	H2Kwinana	105	Western Australia	Ammonia, Sustainable Aviation Fuel, Minerals processing
HIF Asia Pacific Pty Limited	HIF Tasmania eFuel Facility	144	Tasmania	e-Fuels
KEPCO Australia Pty Ltd (Korea Electric Power Corporation)	Port of Newcastle Green Hydrogen Project	750	New South Wales	Ammonia
Origin Energy Future Fuels Pty Ltd	Hunter Valley Hydrogen Hub	Phase 1 – 50 / Phase 2 – 200	New South Wales	Ammonia, Mobility
Stanwell Corporation Limited	Central Queensland Hydrogen Project	720	Queensland	Ammonia
Murchison Hydrogen Renewables Pty Ltd as trustee for Murchison Hydrogen Renewables Project Trust	Murchison Hydrogen Renewables Project	1,625	Western Australia	Ammonia

Source: Australian Government - ARENA

GUARANTEE OF ORIGIN SCHEME

The Australian Government pledged A$38.2 million[66] for the Guarantee of Origin (GO) scheme which, while not exclusive to hydrogen production, is a program which will apply to all clean energy products and assess and certify their emissions level. This is a relatively unique approach and will likely stabilise some of the uncertainty around the qualitative aspects of green hydrogen and its full carbon cost.

Participation in the 'GO' scheme is optional and a further A$2.2 million in funding has been provided to assist in the designing and drafting process. The proposed design opened for consultation in September 2023.[67]

NATIONAL AGENCIES AND BODIES

Australia has several key agencies which contribute to facilitating funding and shaping policy:

ARENA (Australian Renewable Energy Agency)	• Established by the Australian Government. • Aims to improve cost competitiveness of renewable. technologies and help Australia meet its emission reduction targets. • Provides knowledge sharing and funding to achieve these targets. • Administers the Hydrogen Headstart Program.
CEFC (Clean Energy Finance Corporation)	• Considered Australia's 'green bank',and aims to invest in the transition to Net Zero by 2050. • Has a A$300 million Advancing Hydrogen Fund which aims to advance green hydrogen cost competitiveness in Australia.[68] • Administers the Clean Energy Innovation Fund which invested A$28.5 million[69] across four hydrogen related transactions during the 2022-2023 year.
AHC (Australian Hydrogen Council)	• The peak industry body for advancing Australia as a hydrogen leader. They often represent the industry to governments and other stakeholders. • Focused on building a sustainable hydrogen industry through three lenses:, economic, social and regulatory. • AHC also runs several working groups and conferences and provides policy papers, submissions and other resources.

OTHER KEY MARKETS

UNITED STATES

While the United States initially lagged behind Australia and much of Europe in their pursuit of hydrogen opportunities, they have since made significant financial and strategic pledges which has solidified their position as an important player in the hydrogen industry. In a strategy paper, released in June 2023, the United States outlines extensive opportunities for clean hydrogen with up to 10 million metric tonnes of output by 2030 and up to 50 million metric tonnes by 2050.[70] Further key points of this strategy are reducing the cost of clean hydrogen and a focus on regional areas as opportunities to spread infrastructure. The introduction of the Inflation Reduction Act (IRA) signals a shift for the United States towards the energy transition and capitalising on the opportunity for manufacturing in the United States[71]. Most of the funding is drawn from significant tax credits. For hydrogen, the Act does not specify a use of certain technique or technology to qualify for funding and credits. Rather, the emphasis is on emissions reduction[72], allowing wider uptake across industries. The total of all policies in relation to clean energy and climate change programs is targeted to be US$369 billion (A$520 billion).[73] In October 2023, the Biden-Harris administration announced they had selected seven regional hydrogen hubs to receive US$7 billion[74] in funding from a different bill, the 2021 Bipartisan Infrastructure Law.

GERMANY

Germany has been a leader in embracing hydrogen, being an early adopter of the strategy dialogue in line with the European Union and subsequently wider Europe. Germany released an initial strategy paper in June 2020, and updated in July 2023. The ambition behind Germany's hydrogen strategy is climate protection as they aim for net zero greenhouse gas emissions by 2045.[75] While not diverging from renewable energy as costs remain high for hydrogen, opportunities have been identified in growing and developing new industry with emphasis on emerging technologies in Germany. Germany is committed to the energy transition and has committed funding through their Recovery and Resilience plan. This funding included EUR€3.3billion for decarbonising the economy, with a particular focus on green hydrogen and EUR€1.5 billion[76] towards all stages of green hydrogen development, including transportation and infrastructure. Following volatility in the oil and gas market, Germany also partnered with Canada in 2022[77] on bilateral green hydrogen co-operation including establishing a supply corridor and Canada exporting hydrogen to Germany by 2025. [78]

JAPAN

Japan has been an early adopter of engaging in the discussion around hydrogen, notably green and blue hydrogen. A 'Basic Strategy for Hydrogen' released in 2017, highlighted Japan's strong prioritisation of reducing the cost of hydrogen to make it a competitive option and increase uptake. The 2017 roadmap outlined a target price of US$3 per kilogram in 2030 reducing to US$2 in 2050.[79] While Japan has continuously engaged in revising and publishing their goals and policies for hydrogen through several papers and announcements, a revised edition of the 'Basic Strategy for Hydrogen' was released in June 2023 after being approved by Cabinet. The revised strategy sets some ambitious targets including increasing annual supply of hydrogen to 12 million tonnes by 2040.[80] Currently, the majority of hydrogen Japan utilises is from fossil fuels, however, into the future they are looking into both green (renewable) and blue (carbon capture) hydrogen options. Japan is also prioritising international partnerships, where necessary, with focus on the green and blue hydrogen being used in a number of forms including transport, industrial uses and for the generation of power to assist in the decarbonisation process. In the revised update, Japan is also looking at the installation target of 15GW[81] of electrolysers, with a focus on Japanese manufacturers, where possible. To achieve these goals and their strategy, the Japanese Government intends to invest ¥15 trillion (US$107.5 billion)[82] in hydrogen strategies and policies to aid the decarbonisation process.

SOUTH KOREA

South Korea released their initial hydrogen roadmap document at the beginning of 2019 with ambitions to shift away from traditional grey hydrogen into a lower carbon intensive approach. A key emphasis, which stands apart from many other nations, is their pledge towards hydrogen fuel cell vehicles, where, by 2040, South Korea plans to manufacture 6.2 million in addition to 1200 refilling stations.[83] This includes a mix of passenger cars, taxis, buses and trucks. South Korea is likely to be one of the largest export destinations for large suppliers, one of which is likely to be Australia as trade increases between the two nations. In November 2022, the South Korean Government announced plans to create a firmer supply chain to further develop their hydrogen policies. In January 2023, the South Korean government announced US$193 million[84] in funding for six cities to have significant hydrogen investment in fuels cells and various blue hydrogen projects. In 2021, during a visit to Australia by the South Korean President, a strategic partnership[85] was announced by the Morrison government between the two countries for investigation into clean energy, including green hydrogen. The South Korean government has also created a Hydrogen Generation Bidding Market where producers produce power with hydrogen or hydrogen compounds (including ammonia) can sell their power to operators, both regional and the Korea Electric Power Operator. Korea Power Exchange have selected some winning bidders and this could drive demand in Australia.

WHAT ELSE IS HAPPENING AROUND AUSTRALIA?

Victoria	Victoria is engaged in the hydrogen dialogue with the 'Victorian Renewable Hydrogen Development Plan', which is aligned with the National Hydrogen Strategy. Victoria's blueprint outlines the opportunity for hydrogen, including the potential for 7,600 jobs and A$11 billion added to the economy annually.[86] Moving forward, the establishment of hubs and sector coupling is a key priority for the plan in Victoria. In Victoria, the Hydrogen Park Murray Valley located in Wodonga is a key project which has received A$12.3 million in funding from the Victorian Government in addition to the A$36 million[87] from the Australian Renewable Energy Agency (ARENA).
New South Wales	New South Wales places significant value on green hydrogen in their October 2021 'NSW Hydrogen Strategy' report. They also have a 'Net Zero Industry and Innovation Program' report which ties in with NSW's shift to reducing carbon emissions. Key priorities include reducing the cost of green hydrogen significantly, to under A$2.80 by 2030 with up to A$3 billion in funding to provide incentives for development in this area. NSW is aiming to produce 110 tonnes of annual green hydrogen and having 700MW of electrolyser capacity by 2030.[88] Key initiatives NSW has supported are the Hume Hydrogen Highway Initiative which is a refuelling network project. NSW also undertook a Hydrogen powered bus trial in 2023 to determine how hydrogen can be used as a fuel source in the future.[89] It has also pledged A$25 million[90] to support a Hydrogen Centre of Excellence to help train plumbers in hydrogen specific skills.
Western Australia	Western Australia (WA) released their Renewable Hydrogen Strategy in 2019. This strategy emphasised the importance of hydrogen development to the state as a dedicated Renewable Hydrogen Unit was put into place. A$10 million was also pledged over four financial years in the Renewable Hydrogen Fund. This commenced 2019-2020. The strategy outlined some key focuses for WA. These are export, remote applications, hydrogen blending in natural gas networks and transport. In August 2020, the WA Government announced A$22 million for nine initiatives for the future of renewable hydrogen, in line with their Covid- 19 Recovery Plan. The WA Government have continued to invest in renewable hydrogen with a further A$50 million announced as a part of the 2021-22 budget and A$117.5 million for the Pilbara and Mid-West based renewable hydrogen hubs. This aims to establish WA as a clean energy hub and attract federal government funding. The 2022-2023 Budget, released in October 2022, confirmed that several WA projects would be receiving funding through the Commonwealth Government's Regional Hydrogen Hubs program. Key WA recipients of Hub Implementation Grants in WA are bp Australia's H2Kwinana Clean Hydrogen Industrial Hub and Western Australian Government's Pilbara Hydrogen Hub. Each of these projects have been granted up to A$70 million. The WA Government is currently looking at refreshing its strategy, as announced in September 2023.[91]

South Australia	South Australia embraced hydrogen early when releasing their hydrogen strategy paper in 2019, the South Australian 'Hydrogen Action Plan'. They outlined five key pillars within the plan. South Australia believes they are set up to be a green hydrogen leader as they already have the land, sun, wind and much of the infrastructure required. SA are prioritising hydrogen infrastructure investment while integrating the energy system to support hydrogen. SA is also emphasising the importance of trade and supply relationships while putting value investing in the workforce and innovation with a sound and robust regulatory framework in place. To date, SA have made approximately A$15 million in grants and A$25 million in loans to megawatt scale hydrogen projects[92] including AGIG's Hydrogen Park and H2U's Eyre Peninsula Gateway Project.
Queensland	Queensland's hydrogen strategy report the 'Queensland Hydrogen Industry Strategy 2019-2024' was released in 2019 with targets for 2030. The strategy seeks to outline goals to support innovation and public and private sector investment. Queensland is also looking to build community awareness around hydrogen while enhancing a policy framework and developing the skill set for the workforce in Queensland. The Queensland Government has committed funding through the 'Queensland Hydrogen Industry Development Fund' which has now committed A$35 million to several hydrogen related projects. The 'Queensland Renewable Energy and Hydrogen Jobs Fund' now has funding of A$4.5 billion. Hydrogen projects which have been granted funding include A$28.9 million for the Kogan Creek Renewable Hydrogen Demonstration Plant and A$15 million to a Gladstone based large-scale hydrogen export project.
Tasmania	The Tasmanian Government have expressed their intention for investment in green hydrogen through their 'Tasmanian Renewable Hydrogen Action Plan'. Released in 2020, Tasmania had ambitions to produce and use hydrogen locally by 2024 and export hydrogen by 2027[93]. Tasmania is funding this plan through the 'Tasmanian Renewable Hydrogen Industry Development Funding Program'. Through this program, the Tasmanian government is providing A$50 million[94] for hydrogen related projects and programs.
Northern Territory	The Northern Territory (NT) 'Northern Territory Renewable Hydrogen Master Plan' was released in October 2021. The plan is broken up into stages where they will research, plan and trial before active hydrogen projects with the last stage being export. The NT has identified renewable hydrogen as a key industry to assist in the transition as they aim to be net-zero by 2050.[95] The NT Government has committed A$5 million[96] in funding over a four-year period, in June 2022. This funding aims to grow the hydrogen industry in the Northern Territory. Also in 2022, the NT Government signed a Memorandum of Understanding regarding development of the Darwin H2 Hub project with Total Eron.[97]
Australian Capital Territory	The Australian Capital Territory (ACT) aims to be net zero emissions by 2045 and in 2020 announced that green hydrogen will be a key factor in achieving this goal.[98] The ACT are well underway in their journey towards the expansion of the green hydrogen industry with projects including a test facility which looks at the gas network and how it can decarbonise, a hydrogen refuelling station and a renewable hydrogen cluster.

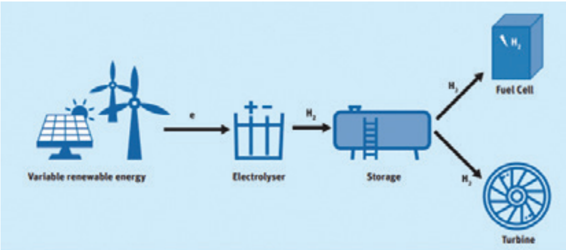
END USES

HYDROGEN END USES

PURE HYDROGEN

LARGE SCALE ELECTRICITY GENERATION

If proved to be commercial against other low carbon solutions, a key potential use of clean hydrogen is for large scale electricity generation. There are two key methods to generate electricity from H_2: fuel cells and gas turbines.[99]



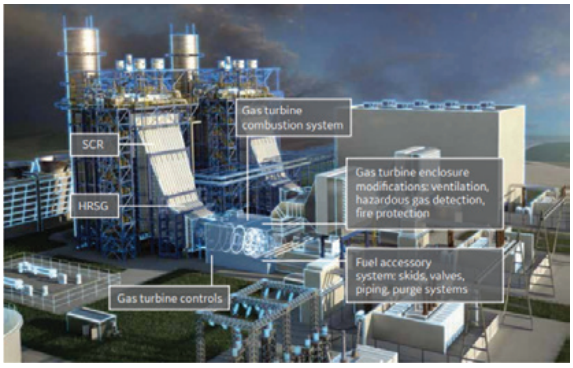
Large scale hydrogen-based electricity generation pathways (csiro.au)

H_2 fuel cells have the capability to provide kilowatts to megawatts of power depending on stack size. On the other hand, the potential power output of H_2 gas turbines is far greater, making them suitable for more centralised applications (>100MV) and a promising candidate to replace existing fossil fuel baseload.[100]

The combination of significant solar and wind sources with industrial-scale H_2 gas turbines would enable a fully decarbonised power system. H_2 could eventually play the vital role of storing energy generated by renewables during periods of oversupply and providing that energy back into the grid when there is a renewables shortfall, acting as a sustainable source of backbone power.[101]

But switching to hydrogen-powered baseload is not as simple as just changing the fuel source at current gas turbine plants. H_2 has different combustion characteristics to traditional hydrocarbon fuels, posing unique challenges for its use in current turbine configurations. For example, the higher flame speed of H_2 increases the risks of flashback in the combustion process, raising the potential for damage to hardware and equipment.[102] Flashback is the phenomenon whereby flame travels toward fuel and air injection locations, destabilising the combustion process. In addition, complications arise from the heighted NOx emissions created by the high flame temperatures of H_2, with some estimates suggesting turbine NOx emissions may double if operating on 100% H_2.[103] There are also safety concerns given H_2 is more flammable than natural gas and difficult to transport and store.[104]

Existing gas turbine plants would likely require modifications to the combustion, emissions scrubbing, ventilation, sensor, electrical and fuel supply systems, with the addition of back-up storage infrastructure, to adopt H_2 as fuel.[105]



Potential impact of H_2 fuel on existing gas power plants (ge.com)

The extent and cost of the modifications required primarily depends on the age of the facility and the level of hydrogen desired in the fuel blend.[106]

Concept of RWE's and Kawasaki's hydrogen-to-power- plant in Lingen (left) and a Kawasaki Heavy Industries hydrogen gas turbine (right) (kawasaki.com)

While industrial-scale pure hydrogen gas-powered turbines are not currently operating, companies are focusing on their development. Kawasaki Heavy Industries and RWE Generation are developing a pilot plant to test 100% H_2 gas turbine power generation. The plant is due to be operating in 2024, noting that Kawasaki Heavy Industries have demonstrated a 1MW 100% H_2 gas turbine before. An interesting feature of the turbines being developed by Kawasaki is that they are designed to be compatible with any blend of H_2 and natural gas, ranging from 100% H_2 to 100% natural gas.[107] Mitsubishi Power is aiming to produce large scale 100% H_2 gas turbines by 2027.[108] Within the Australian context, the SA government, in conjunction with BOC and Atco, are developing a 200MW power plant with 100% H_2 gas turbines, noting a supplier of the turbines has not yet been chosen.[109] The current challenges in commercialisation of H_2 gas turbines centre on the technical complexities created by the high combustion speeds, temperatures and associated nitrous oxide emissions of H_2.[110]

Another potential use of H_2 in large scale power generation is through ammonia cofiring at existing coal power stations. This technique is currently being investigated in Japan and Korea and is discussed in a subsequent section specifically dedicated to ammonia.

GAS BLENDING

In the intervening time before the commercialisation of industrial-scale pure H_2 gas-powered turbines, blending renewable H_2 into existing natural gas energy systems offers a viable alternative to reduce emissions. This concept is commonly referred to as hydrogen-enriched natural gas (HENG) and already deployed in town gas networks within geographies such as Singapore, Hong Kong and Hawaii.[111] The US, European Union and South Korea are currently pursuing initiatives to increase the use of H_2 in their existing networks, with many OEMs already producing turbines that can run on hydrogen-blended fuel.[112] HENG is also currently undergoing multiple trials within Australia.

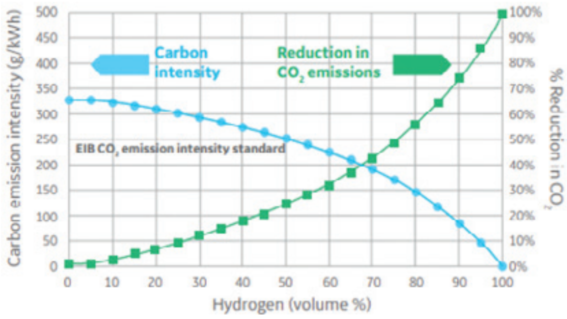
Australia – Operational Hydrogen Gas Blending Projects	
Clean Energy Innovation Hub – ATCO	H_2 produced from electrolyser powered by solar energy. H_2 production distributed into a demonstration facility, consisting of a microgrid including a display home and 200kW gas generator. Blending volume target of 10% H_2.
Hydrogen Park South Australia – Australian Gas Networks (AGN)	Renewable H_2 produced via 1.25MW Siemens PEM electrolyser, blended with natural gas at concentrations of 5% into existing gas network in Metropolitan Adelaide. Achieved supply to approximately 4000 homes and businesses in March 2023.
Hydrogen Test Facility – ACT Gas Network	1.25KW alkaline electrolyser powered by solar panels. H_2 production distributed into a replica network for infrastructure and appliance testing – initial results suggest an off-the-shelf cooktop can tolerate blends of up to 20%.
Western Sydney Gas Project	500kW electrolyser powered by renewable energy. H_2 production injected into Sydney secondary gas distribution network at concentrations of up to 2%, with first blending in November 2021.

Source: CSIRO – HyResource

The blending of H_2 with natural gas primarily reduces emissions through the reduction in the CO_2 intensity of the gas mixture but also through the impact on natural gas conversion efficiency.[113] The addition of even small amounts of H_2 into a gas stream can lead to more complete combustion, reducing toxic pollutants.

H_2 can be blended into existing gas networks without modifications at concentrations typically ranging between 5% to 20%, rendering the emissions reductions quite cost-effective.[114] Studies from the HyDeploy project in the UK suggest that higher concentrations require modifications to plants, distribution networks and domestic appliances for operational and safety reasons.[115] For reference, estimates indicate that a blend of 20% equates to CO_2 savings of approximately 7% vis-à-vis pure natural gas.[116] The benefits in terms of emissions reductions are expected to be greater for those geographies that rely heavily on natural gas heating systems.[117]

To facilitate the adoption of higher concentrations in gas systems, governments would need to legislate standardised requirements for infrastructure through to household heating systems and appliances. The required retrofitting under such a scenario would be significant. Electrification of household heating systems and appliances is more likely, particularly in jurisdictions like Australia where some governments have banned gas connections to new homes.[118]



Relationship between H_2 fuel and CO_2 emissions for a 9H.02 gas turbine (ge.com)

Regardless, blending clean H_2 into existing gas infrastructure not only provides a path to lower emissions, it also offers an avenue to efficiently distribute H_2 from production centres. However, the ability to utilise existing gas transmission networks is dependent on the development of commercially viable deblending and purification technologies[119], noting there has been progress towards this goal recently. Linde has commissioned a full-scale demonstration plant in Germany capable of producing high purity H_2 from blends of 5% to 60% using specialised membrane technology.[120]

HARD TO ABATE GEOGRAPHIES AND SECTORS

Pure H_2 is likely to be key for hard to abate geographies and sectors.

H_2 IS LIKELY TO BE KEY FOR HARD TO ABATE GEOGRAPHIES AND SECTORS.

Hard to abate geographies are those which lack abundant solar, wind and/or land resources and thus cannot significantly rely on wind and solar for their energy supply. H_2 can enable such geographies to decarbonise through its ability to act as a transport vector, moving energy from locations with abundant renewables to those with deficits. For example, due to land availability constraints and a consequent inability to develop sufficient renewables, Japan plans to replace its significant fossil fuel imports with H_2 mainly sourced from Australia to reach its 2050 targets.[121] Estimates suggest this is a more cost-effective solution for Japan than generating green H_2 itself.[122]

Hard to abate sectors, such as aviation, iron, steel and cement, are those which typically rely on fossil fuels for high-temperature energy or as chemical feedstocks.[123] For these sectors, current electricity-based solutions come with technical limitations or prohibitive costs. Hydrogen can enable these sectors to decarbonise because it can be combusted and chemically reacted in ways that are similar to fossil fuels without the associated CO_2 emissions.[124] For example, in the case of steelmaking which accounts for approximately 6-9% of global CO_2 emissions[125], H_2 may be able to replace the use of coking coal in blast furnaces and drive substantial emissions reductions.

For these geographies and sectors to adopt H_2 as a major energy source, many developments around the production, transportation, storage and utilisation of H_2 are still needed. To facilitate such developments, governments across the globe have implemented a multitude of policy measures to support hydrogen investment, with initiatives particularly focused on hydrogen solutions for hard to abate sectors.[126]

MOBILITY & FUEL CELLS

HYDROGEN-BASED TRANSPORTATION

Many countries have already announced their intention to phase-out thermal internal combustion engines (ICEs) in the near future. H_2 mobility could therefore become part of the solution and it is expected that by 2050, 113 million fuel-cell electric vehicles (FCEVs) could be on the road.[127] This could save up to 68 million tonnes of fuel and almost 200 million tonnes of carbon emissions[128], making a significant contribution to reducing energy consumption and GHG emissions within the transport sector.

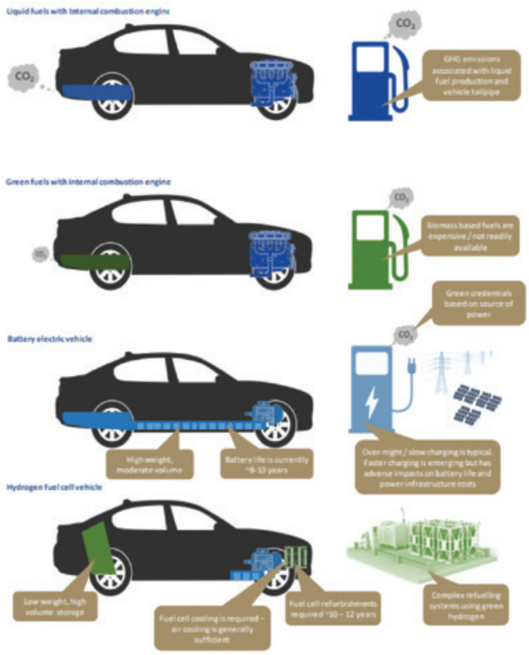
H_2 can be used in fuel cells to efficiently generate electricity for an electric vehicle, or can be converted into a denser form (such as ammonia, methanol and synthetic fuel) for use in ICEs. Unlike in some sectors, H_2 already has a decarbonised competitor in lithium-ion batteries. Battery costs have fallen by ~90% since 2008, helping to spur demand and increase total market share for battery electric vehicles (BEVs).[129] H_2 FCEVs, by comparison, are currently a more expensive alternative still in development phases, with only ~72,000 in global stock at the end of 2022.[130]

The H_2 mobility sector spans several end-uses for FCEVs including light passenger vehicles, buses, heavy- duty trucks, material handling, ferries, marine shipping, aviation, and other associated infrastructure such as refuelling stations.

Currently, the CEFC has found only line-haul, material handling and return-to- base vehicles (including buses) to be commercially viable for H_2 FCEV applications.[131] All other potential forms of H_2 transport require lower H_2 supply, storage and dispensing costs to become competitive with battery or fossil-fuel alternatives.

To further unlock the potential of H_2 FCEV mobility applications, an integrated approach will be required including increased policy support (either through quantitative targets or specific funding for mobility applications), full supply chain coordination between H_2 production to refuelling infrastructure providers, and supportive regulatory frameworks to facilitate new transport fuels and vehicles.

The main differences between ICEs, BEVs and FCEVs are outlined below:



Differences between vehicle technologies (cefc.com.au)

EVs are already competing with their ICE counterparts in some markets, with the key reasons being centred around lower fuel costs, reduced emissions, easier automation, and higher torque and acceleration.

In terms of how fuel cells themselves work, instead of combustion, they produce electricity via an electrochemical reaction that combines H_2 and oxygen to generate an electric current with water as a by-product. This process is the reverse of an electrolysis procedure, and the cell stack is typically accompanied by a H_2 storage tank pressurised to 700 bar.[132] Fuel cells are preferable to traditional combustion engines as they are quiet, emissions free, and can yield substantially greater energy efficiency.[133] Furthermore, FCEVs can compete against BEVs from a technical standpoint in that they have faster refuelling times, higher energy storage densities and lower space requirements, rendering them potentially more suitable for consumers who travel longer distances (i.e. 400-600km without refuelling).[134]

Safety

By their nature, all fuels have some degree of danger associated with them. However, in outdoor environments, a number of H_2's properties make it safer to handle and use in comparison to other commonly deployed fuels.

H_2 is non-toxic, and due to its light density, dissipates quickly when released, enabling relatively rapid dispersal in the case of a leak.[135] Furthermore, the vapours of H_2 do not pool on the ground (unlike gasoline), which presents less of a threat of fire or explosive danger. To further minimise this potential, almost all H_2 fuel stations store the gas above ground in well-ventilated areas.

The manufacturing of fuel cells does require additional engineering controls to ensure safe use. This is primarily aimed at mitigating flammability risk. Adequate ventilation alongside flame detectors, tank leak tests, garage leak simulations, and H_2 tank drop tests are standard in the design of safe H_2 systems.[136] FCEVs themselves have arrays of H_2 sensors that sound alarms, and seal valves and fuel lines in the case of a leak.[137] The pressurised tanks that store the H_2 have also been found to be safe in collisions through repeated testing.[138]

TRANSPORTATION USE CASES

Material handling

FCEVs are already seeing a fast uptake in the material handling sector and are competing directly with BEVs due to their low noise, low pollution, and faster refuelling times. Additionally, in large warehouses with 24/7 operating requirements that currently rely on battery driven equipment, the switch to FCEVs reduces both the capital costs and storage space issues associated with the purchase of replacement batteries. The risk of warehouse inventory being potentially damaged by odours released in the battery recharging process is also removed with FCEVs.

The most common material handling FCEV is that of forklifts, in which H_2 can power lift capacities of 4,000-5,000kg. FCEV forklifts are also able to be refuelled in as little as three minutes, which saves significant downtime compared with battery-operated forklifts that can take up to eight hours to recharge.[139]

The key barrier to the adoption of hydrogen-powered vehicles in Australia is a lack of hydrogen infrastructure (i.e. refuelling stations).[140] However, due to their wide-reaching benefits, FCEVs are becoming much more attractive in these types of operations with demand picking up considerably.[141]

Hydrogen fuel cell forklifts by Toyota (h2-view.com)

Heavy-duty vehicles

Although H_2 hasn't taken off in the automotive industry as yet, several established manufacturers (including Hyzon, Hyundai, Toyota and Daimler, among others) are exploring the potential for FCEVs in the heavy-duty transport sector to make commercial vehicles greener.[142]

The heavy-duty vehicle sector in Australia is subject to subtly different influences compared to other countries around the world. These include competition with rail, potential exposure to extreme environmental conditions, and the demand for fast refuelling times throughout long-haul/interstate journeys.

Heavy-duty vehicles such as mining trucks, line-haul trucks that deliver goods on a fixed route, or buses that return to their base frequently, can be powered by H_2 at dedicated refuelling stations, which would consequently reduce distribution costs - making H_2 more competitive with diesel.

Further advantages for H_2 within heavy-duty vehicles include a reduced barrier to refuelling infrastructure as travel routes and driving ranges are predictable. And H_2 FCEVs can contain a higher amount of energy-per-unit of mass than a lithium battery or diesel fuel – meaning a truck can have a higher amount of energy available without significantly increasing its weight. This is an important consideration for long-haul trucks subject to weight penalty policies.

Rail

With only 11% of Australia's railway tracks currently electrified[143], hydrogen-powered rail could have a place in future infrastructure considerations. After completing successful trials, 36 Alstrom H_2 fuel cell locomotives are now operating in Germany as of June 2023. Countries including China, Japan, Canada, Spain and Italy are also conducting trials or have orders for H_2 fuel cell locomotives.[144] With rail FCEVs having the opportunity to be comparable in cost to that of electrification, H_2 technology will be most competitive for services requiring long distance movement of large trains with low-frequency network utilisation, or cross-border freight.[145] This is a common set of conditions in the needs of Australian rail freight, therefore presenting an opportunity for H_2.

Ferries

Ferries are a marine shipping case where the requirements for fuel storage are significantly less than for coastal or international shipping. Ferry journeys are often only a few hours in duration, or in the case of commuter ferries – a daily operation. This provides the opportunity for at least daily refuelling. The consequence of lower fuel storage is the likely preference for lower cost/higher efficiency fuels as opposed to those that offer the highest energy density. Gaseous and liquid H_2 have much lower volumetric energy density than Marine Gasoil (MGO) but are significantly more energy dense than batteries.[146] Use of hydrogen-derived fuels, such .as ammonia and methanol, will require reciprocating engine technology until direct ammonia and methanol fuel cells are commercialised. Therefore, in current times, the demand for H_2 fuel cells in marine transportation is highly dependent on the individual preferences of consumers.

Maritime

Shipping has limited low-carbon fuel options available; 98.8% of the global fleet is currently sailing on fossil fuels.[147] As discussed in a later section of this report, there is a substantial opportunity for H_2-based fuels but H_2 fuel cell-powered maritime freight may also gradually emerge, with Samskip placing two orders for the world's first hydrogen-powered container ships in late 2023.[148] Maritime freight is set to grow by 2030, providing an incentive for the sector to transition into the use of H_2 fuel cells to facilitate decarbonisation.

Aviation

There is significant pressure on the airline sector to decarbonise in order to retain its social license to operate given it is responsible for ~2.5% of global carbon emissions.[149] The industry is actively seeking commercially viable solutions to reduce carbon emissions, presenting an opportunity for H_2. As with the maritime sector, fuel cells are beginning to be adopted by Unmanned Aerial Vehicles (UAV) or drones to power propulsion mechanisms.[150] Fuel cells can provide eight-10 times more flight time in some UAV models and have shorter refuelling times than batteries.[151]

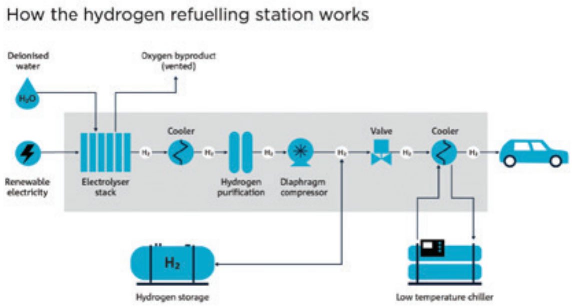
In terms of manned aircraft/passenger aviation, application of fuel cells to this sector appears to be quite distant given the current energy requirements. That said, there is potential for regional flights (20-80pax, within a 1000km range) to make use of electrically-driven turbo props.[152] At this stage, longer haul flights are likely to use jet engines fuelled by sustainable aviation fuel (SAF), at least until 2050.[153] Renewable H_2 is expected to be a key input for SAF production.

RENEWABLE H_2 IS EXPECTED TO BE A KEY INPUT FOR SAF PRODUCTION.

There are also plans to use clean H_2 in the space industry. Hypersonix Launch Systems intends to deploy green H_2 produced by BOC in Australia as rocket fuel to launch re-useable satellites carrying payloads into lower earth orbit.[154] Similar efforts to reduce the carbon emissions associated with the launch of satellites are underway in Europe.[155]

INFRASTRUCTURE REQUIREMENTS

A hydrogen refuelling station (HRS) consists of a standard overall system that can vary in hydrogen delivery method, dispenser pressure, and capacity, which consequently affect its configuration and costs. H_2 can be delivered in gaseous or liquid form, with liquid form necessitating a cooling system in the configuration.[156] Control systems are necessary to monitor volume, temperature, flow rate, and pressure, all of which require high electricity levels to regulate. According to recent estimates from the US, a HRS with a capacity of 1,240 kg/day has an average development cost of US$1.9m.[157] However, the installation of H_2 refuelling infrastructure has picked up momentum in the past few years, driving cost reductions that are expected to continue.



A refuelling station (csiro.au)

The costs of building and operating refuelling stations are aimed to be repaid by fuel sales over the lifetime of a station. If the ratio of refuelling stations to cars were similar to today's oil-powered car fleet, for every 1 million H_2 FCEVs, over 400 refuelling stations would be needed to service the fleet. This compares to the requirement of ~30,000 public charging points per 1 million BEVs.[158]

ActewAGL refuelling station in Canberra, ACT (act.gov.au)

The infrastructure to support hydrogen-powered vehicles in Australia is developing as the technology becomes more widespread and the demand for low-emissions technology ramps up. Neoen and ActewAGL opened Australia's first H_2 vehicle-refuelling station in Canberra during 2021, marking a major milestone in the roll-out of FCEVs. The ACT government is utilising the station to service its new fleet of Hyundai Nexo H_2 cars, as part of its efforts to decarbonise. The station can produce 21kgH_2/ day and store 44kg.[159]

Other refuelling stations in operation include the Toyota Hydrogen Centre in Melbourne, the ATCO Australia/FMG hub in Perth and BOC's Port of Brisbane and Coregas's Port Kembla facilities. There are six refuelling stations due to complete construction in 2024, with production capacities ranging from 20 kg/day to 1000 kg/day. Other major Australian projects focused on refuelling infrastructure include the Hume Hydrogen Highway, which has received funding from both the NSW and VIC governments, is expected to be complete in 2025.[160]

COST CHALLENGES

Transport, storage, handling and dispensing all add costs. Currently, H_2 at an Australian HRS has a price tag between $6.78/kg and $15.60/kg depending on the HRS configuration and throughput. Interestingly, estimates of H_2 supply at the lower end of this range require production of H_2 offsite, with transport of H_2 gas to the HRS via road. Even at $6.78/kg, costs still need to fall substantively to achieve parity with gasoline.[161]

In addition to the cost of installing/operating HRS infrastructure, the commerciality of H_2 FCEVs depends on how the following components develop compared with their present and potential future competitors:

The cost of the fuel cell stack

The current commercial cost of a typical fuel cell is estimated to be ~A$250/kW.[162] However, research into technological advancements and cost component reduction is aiming to bring this amount down, especially as manufacturing of cell stacks benefit from economies of scale.

Research and development activities suggest it may be possible to increase catalyst activity of the cell stack and therefore reduce or eliminate the platinum content, which is currently the most expensive component of a cell stack.[163] Furthermore, cost reductions in the bipolar plates, compressors and humidifiers are all expected to occur as demand ramps up for FCEVs into the future.

The culmination of these expected cost reductions will result in downward pressure on the price of a fuel cell, and it is expected to reduce by 20% to ~A$200/kW by 2025.[164]

The cost of on-board storage

On-board storage of H_2 necessitates compression or liquefaction due to the low volumetric density of H_2. These methods consume 5-15% and more than 30% of the lower heating value of H_2 respectively.[165]

COMPONENT MANUFACTURERS

Category	Company (non-exhaustive list)			
Compression	• Mehrer • LW Compressors • PDC	• Sauer Compressors • Neuman & Esser • RIX	• Nash • Brotie	• Howden • Flowserve
Liquefiers	• Kawasaki Heavy Industries	• Air Liquide	• Linde	• Plug Power
LOHC Technologies	• Hydrogenious	• Hynertech		
Cooling Systems	• KUSTEC Kalte-Und System Technik GbmG	• Sterling Thermal Technology		
Storage	• GKN Hydrogen • Hydrexia	• Hexagon Purus • Hydrogenious	• HPS • LAVO	• NPROXX • Worthington Industries
Trailer Manufacturers	• Calvera • Chart	• Weldship Corporation	• Linde • Wystrah	• CIMC ENRIC
Fuel Cell	• ULEMCo • Plug Power	• SFC Energy • NPROXX	• Fuelcellenergy	
Mobility	• Nikola Motor Company • Hyzon Motors	• Honda • Toyota • Scania	• Volkswagen • Stellantis • Hyundai	• Daimler • Air Liquide

HYDROGEN-BASED FUELS

Hydrogen-based fuels include derivative products such as synthetic methane, ammonia and methanol. Interestingly, 60% and 30% of the 53Mt of H_2 used in industry during 2022 was for ammonia and methanol production respectively. Almost all of this H_2 was grey.[166]

SYNTHETIC METHANE

At present, methane is used by industry for ammonia production, power generation and in alumina, iron and steel smelters, being the main component of natural gas. Other industrial applications include the production of fabrics, plastics and anti-freeze.[167] In residential and commercial settings, methane (i.e. natural gas) is used for heating and cooking. While most methane utilised today is currently in the form of natural gas, 'synthetic' methane or 'e-methane' can be manufactured.

Synthetic methane is a potential transitionary fuel and carrier of H_2.

The production of synthetic methane involves combining CO_2 with H_2. Although the burning of synthetic methane still produces emissions, it is thought to be a cleaner fuel than traditional natural gas if produced with renewable energy in conjunction with CO_2 captured from renewable biogenic sources, combustion sources or the atmosphere. Systems that capture emissions at the point of use (i.e. combustion sources) and reuse them to make more synthetic methane would be carbon neutral. Therefore, given its compatibility with existing gas infrastructure, synthetic methane may help smooth the path to net zero.

Methane molecule with central carbon atom surrounded by 4 hydrogen atoms (nature.com)

That said, production methods are still relatively inefficient, with the traditional Sabatier process yielding an energy input-to-output efficiency between 50-60% after accounting for H_2 production via electrolysis. New methods involving the production of hydrogen and methane within a single device are currently under trial, hoping to achieve efficiency rates of up to 80%.[168]

AMMONIA

Seventy percent of today's ammonia is currently used for fertilizer production, with the balance used for refrigeration, pharmaceuticals, textiles, plastics and explosives.[169] As emissions regulations continue to tighten and fossil fuel sources are phased out, there is likely to be significant demand from the ammonia industry for low-carbon H_2. At present, the ammonia industry is reliant on grey H_2 produced from natural gas. Moreover, conversion of hydrogen to ammonia may mitigate many of the technical challenges related to the transportation, storage and utilisation of hydrogen.

Notably, ammonia can be liquified at higher temperatures (-33°C at atmospheric pressures) and lower pressures (above 7.5 bar at 20°C) than H_2. Ammonia also has lower boil off rates at 0.025 vol%/day versus that of H_2 at 0.520 vol%/day. At the same time, the energy density of liquified ammonia is approximately 50% higher than that of liquified hydrogen.[170]

- Liquified ammonia: 3.83MWh/m3
- Liquified hydrogen: 2.64MWh/m3

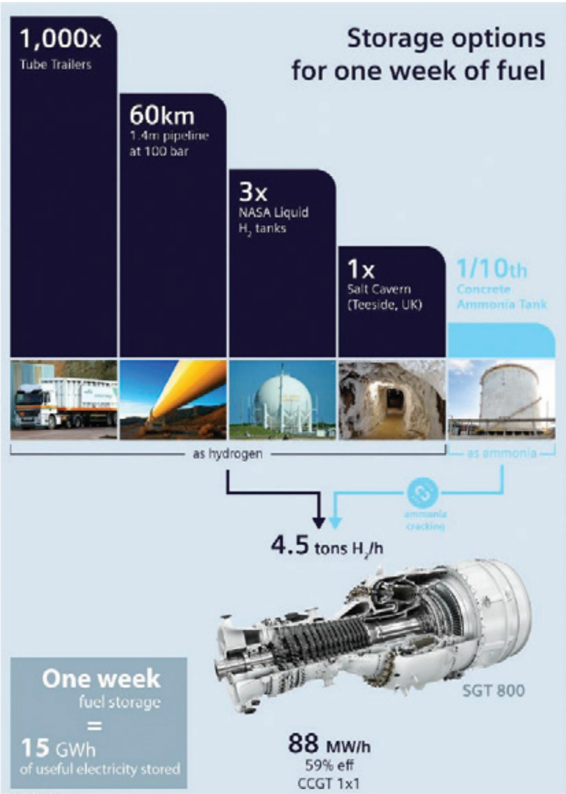
Ammonia can be created via the Haber-Bosch process which involves combining nitrogen gas with hydrogen at high temperatures and pressures. The hydrogen storage capability of ammonia is significant given that it is 17.6% hydrogen by weight.[171] The H_2 component of ammonia can be extracted by heating it to temperatures above 900°C. While ammonia presents several benefits, ammonia synthesis via the Haber-Bosch process and the required cracking of ammonia at its point of use is energy intensive, posing further challenges to the development of a hydrogen economy.[172]

Estimated return on energy investment for different H2 storage and transport pathways

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Hydrogen Production	Electrolysis	Electrolysis	Electrolysis	Electrolysis	Electrolysis
Ammonia Production				Haber-Bosch	Haber-Bosch
Storage and Transport	Compression	Liquefaction (7 days)	Liquefaction (182 days)	Liquefaction (7 days)	Liquefaction (182 days)
Conversion				Cracking	Cracking
MWh required per t-H2	39.7-52.7	50.5-63.5	73.5-86.5	63.7-78.3	65.1-79.75
Overall return on energy investment	63-84%	52.5-66%	38.5-45%	42.5-52.3%	41.8-51%

Source: University of Pennsylvania – Kleinman Center for Energy Policy

The economics of liquifying H_2 versus storing it in ammonia depends on the required storage duration due to the different boil-off rates of H_2 and ammonia. At an energy cost of 40 MWh/t-H_2 for electrolysis, 60MWh/t-H_2 for renewable ammonia synthesis and 8 kWh/t-H_2 for ammonia cracking, there is a break-even threshold between the two methods of 11 days, with liquifying H_2 being more cost effective before this point.[173] While it is important to note that changes to the aforementioned efficiency rates would drastically change the break-even threshold, most freight voyages range between 20 and 45 days.[174] Therefore, ammonia may be the dominant form of H_2 trade between countries, particularly if the energy efficiency of hydrogen-based ammonia synthesis and cracking technology improves. According to some estimates, ammonia trade may increase 10-fold by 2050.[175]



Comparison of H_2 storage methods (siemens-energy.com)

Indeed, the use of ammonia directly as a fuel source for large scale power generation is being investigated due to its carbon-free properties and ability to enable the continued utilisation of existing coal-fired power plants. A Japanese power generator, JERA, is currently trialling cofiring ammonia with coal at concentrations of 20%, with plans to increase this to 50% by 2028.[176] Similarly, China has demonstrated cofiring with ammonia at concentrations of 35%. Note that the emissions reductions benefits associated with ammonia cofiring are directly related to the ammonia-content of the fuel source. However, some believe that cofiring coal with clean ammonia may not be the best method of decarbonisation for countries like Japan, with estimates of a \$136/MWh minimum LCOE at 50:50 fuel concentrations in 2030 versus that for solar with co-located batteries at \$89/MWh.[177] The difference in costs is largely driven by those incurred to produce clean H_2 for conversion into ammonia. There are also retrofitting costs required to make the plants suitable for ammonia, including scrubbing systems to capture heightened NOx emissions.

Another potential direct use of 'green' ammonia manufactured from clean H_2 is as a fuel for shipping vessels. There are currently approximately 40 large ammonia-ready vessels under development, with approximately 90 on order globally.[178]

There are currently several green ammonia projects underway across the globe, with some of these based in Australia.

METHANOL

Today, methanol is primarily utilised as a feedstock in the production of industrial chemicals and consumer products, and as a transport and heating fuel.[179] Like synthetic methane, methanol is created through combining H_2 and CO_2, with CO_2 released following its combustion. Methanol offers similar benefits to ammonia in terms of its ability to act as a transport and storage vector for H_2. It also has similar energy requirements for clean synthesis. As with ammonia, the energy requirements are dominated by the costs to produce clean H_2, not those associated with conversion from and cracking back into H_2.[180]

As discussed in the subsequent chapter, a key benefit of methanol is its liquid-form in ambient conditions. This feature facilitates its cost-effective transportation due to the large availability of suitable vessels (i.e. existing oil tankers) and relatively low storage requirements as it need not be kept at low temperatures like ammonia.[181] Additionally, engine modifications to make shipping vessels methanol-powered are less substantial than those required to make them ammonia-powered.[182]

There are currently ~25 methanol-ready vessels under development/demonstration globally, with orders for methanol vessels from companies such as Maersk as part of their decarbonisation efforts. Maersk received its first methanol container ship in July 2023 and is expected to introduce eight more methanol vessels in 2024 alone[183], with a total of 19 currently on order.[184] In response to such developments, ports such as Singapore and Port of Melbourne are building methanol refuelling infrastructure.[185]

Maersk's first methanol-enabled container vessel (reuters.com)

Given that a substantial number of ammonia powered vessels are also under development or on order, it seems there is some contention over which of these hydrogen-based fuels is likely to dominate. Over the longer-term, green ammonia is expected to outcompete green methanol due to the expected lower cost to acquire large amounts of nitrogen feedstock versus CO_2, making it cheaper to produce.[186]

BIOFUELS

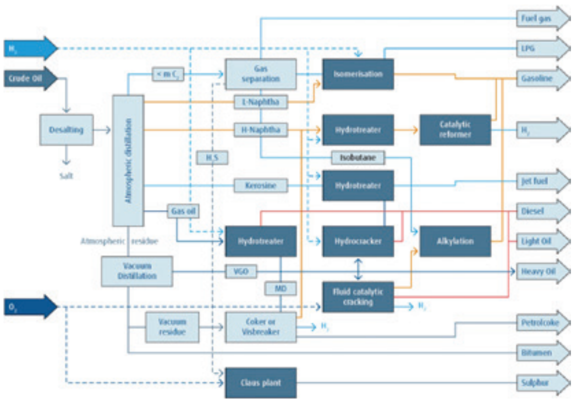
HYDROGEN IN THE REFINERY PROCESS

An existing use of H_2 is in refineries where it is used to 'crack' the long carbon chain of raw oil into a shorter form, which is easier to ignite and more useable as a fuel.[187] H_2 is also used to lower the sulfur content of diesel; this process is called hydrodesulfurization or hydrotreating.[188] As with other existing use (i.e. ammonia production), almost all of the H_2 used in oil refineries is made on-site via steam methane or catalytic reforming.

In recent years, the demand for H_2 across the world's 1000-plus refineries has grown substantially particularly due to the rise in diesel demand and more stringent regulations on sulfur-content. Given the ongoing tightening of environmental regulations and climbing carbon prices, petroleum and diesel producers are facing mounting pressures to decarbonise. The replacement of grey H_2 with clean H_2 in the refinery process is a potential pathway to reduce the carbon intensity of these fossil fuels.

For instance, Irving Oil, a Canadian energy company and a major producer of grey H_2 (~7% of Canada's H_2 production), has plans to produce 2 tonnes of green H_2 per day via a 5MW PEM electrolyser developed by Plug Power. The company estimates carbon emissions will be reduced by up to 6,500 tonnes a year through this initiative.[189]

While the use of clean H_2 alone is unlikely to be sufficient for refineries to comply with future emissions regulations, clean H_2 demand from refineries could reach 50Mtpa globally by 2050.[190] To fully decarbonise, refineries will also need to deploy energy from renewables, CCS and potentially switch to low-carbon feedstocks.



The uses of hydrogen in refinery processes (linde-gas.com)

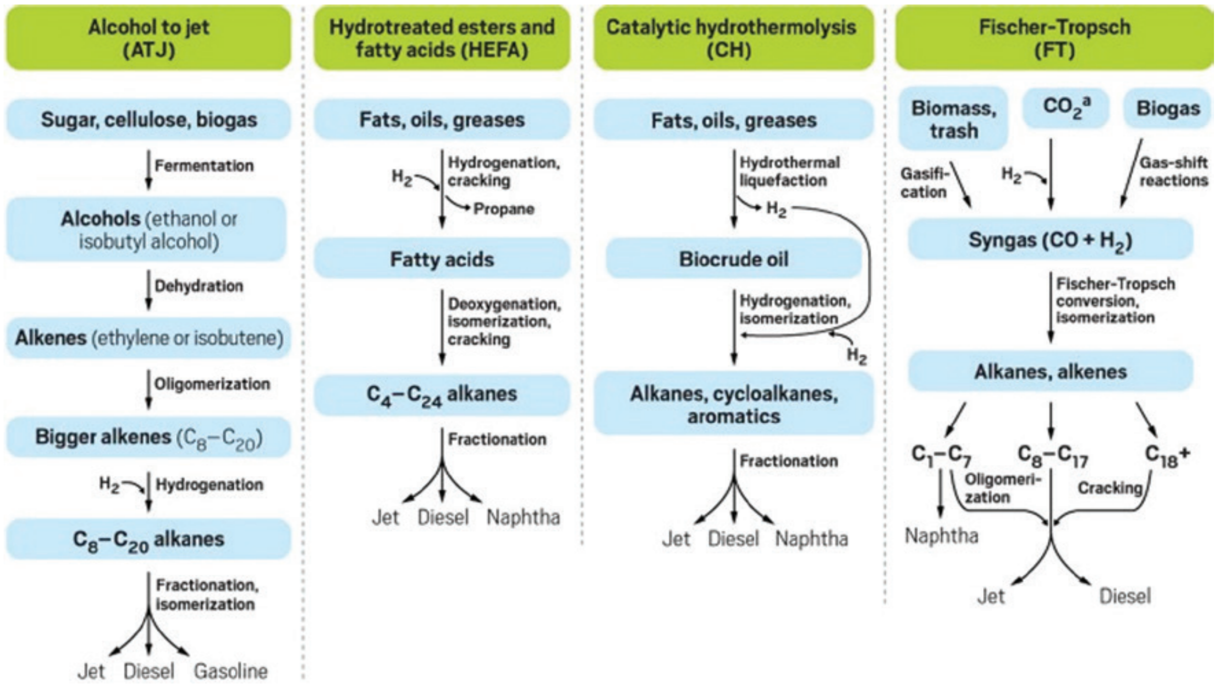
PRODUCING BIOFUELS WITH HYDROGEN

Although conventional petroleum-based fuels will be eventually phased out as carbon prices continue to increase, biofuels may be a major demand source for clean H_2. The combustion characteristics of biofuels are similar to those of petroleum-based fuels but biofuels have significantly lower life-cycle emissions as they are created from feedstocks which sequester carbon during their production. Biofuels currently in use today include renewable diesel, biodiesel, ethanol and, to some extent, SAF.

The key advantages biofuels offer in terms of decarbonisation is their lower carbon intensities and their compatibility with existing engines and infrastructure. These fuels can be blended with or used as an outright substitute for petroleum-based fuels with little to no modifications needed. For example, renewable diesel has, on average, 65% less carbon emissions compared to petroleum-based diesel. At the same time, it is chemically identical to petroleum-based diesel and thus completely compatible with existing infrastructure and engine designs, meeting ASTM D975 and EN 590 specifications in the United States and Europe respectively.[191]

The carbon intensities of different biofuels depends on a range of factors including the particular biogenic material from which it is based, how and where this is produced and the manner in which it is ultimately processed.

According to US DOE, the life cycle emissions of corn-based ethanol produced via a fermentation process (see below) are currently 44-52% lower than gasoline. This range exceeds an earlier estimate of ~20% in the early 2000s, reflecting improved corn farming efficiency (higher yields per acre, less fertilizer) and less carbon/energy intensive production methods.[192] The revision in the US DOE estimate also underscores the complexity of measuring the carbon reductions associated with these fuels. However, depending on the feedstocks and production methods employed, the carbon reductions associated with biofuels has the potential to reach over 90%. The use of clean H_2 in the production process for these fuels will facilitate maximum reductions in emissions.



Different production routes for biofuels (cen.acs.org)

With their 'drop in' capability and the ongoing efforts to decarbonise, there has been a strong rise in demand for biofuels. For reference, the United States consumed more than 40 million barrels in 2022, up from only 12 million barrels in 2019.[193] Further consumption is constrained by the current supply challenges which centre on securing adequate renewable feedstocks; markets are expected to be in deficits until 2027.[194]

Given the opportunity created by these fuels, oil players are rushing to position. Exxon Mobil converted a refinery in 2022 to produce four million barrels of renewable diesel annually based on soybean oil feedstock. In 2024, Exxon Mobil will convert their Strathcona refinery to renewable diesel and utilise canola oil feedstock, with plans for this specific operation to utilise blue H_2 in the hydrotreating process and target production of seven million barrels per year.[195]

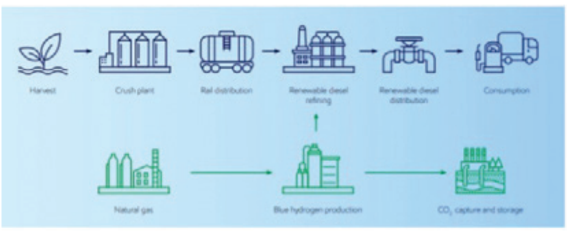


Diagram of ExxonMobil's renewable diesel production process at the Strathcona refinery (exxonmobil.com)

BIOFUELS FOR HARD TO ABATE SECTORS

Biofuels are expected to be especially crucial over the medium term for traditional combustion vehicles that cannot be cost-effectively replaced with cleaner alternatives. Examples of such transport vehicles include mining trucks and airplanes. In the case of mining trucks, estimates indicate that electric mining trucks may be up to 33% less productive than their conventional diesel counterparts[196], underscoring the need for transitionary fuels that can reduce emissions but avoid the current technical deficiencies of electrification.[197]

Companies such as Rio Tinto are adopting renewable diesel, with their Californian Boron operation being the first open pit mine to fully transition to renewable diesel in June 2023. Rio Tinto estimates that the switch will eliminate 45,000 tonnes of CO_2 a year, equivalent to the annual emissions of 9,600 cars.[198]

Biojet fuel or sustainable aviation fuel (SAF) will be key to the decarbonisation of the aviation sector, which contributes ~2.5% of the world's carbon emissions.[199] Sustainable aviation fuel is based on the similar inputs to renewable diesel and biodiesel. SAF may be able to reduce the lifecycle emissions associated with aviation by up to 80% but its uptake is currently limited due to the presently high production costs of SAF.[200] Notably, the first 100% SAF-powered transatlantic trip for a large commercial flight occurred in November 2023.[201]

BP has projects focused on the production of renewable diesel and SAF, including one in Kwinana, Australia. Across their current projects, BP is currently targeting SAF production of 50,000 barrels a day by 2030.[202] A key offtaker of this supply will be global logistics company, DHL, which has plans to use 10% SAF by 2026.[203] Qantas intends to replace its current jet fuel consumption with 10% SAF by 2030.[204]

GREEN STEEL

Steel is one of the core pillars of today's society and, as one of the most important engineering and construction materials, it is present in many aspects of our lives. However, the industry now needs to cope with pressure to reduce its carbon footprint from both environmental and economic perspectives.

CONVENTIONAL STEELMAKING TECHNOLOGY

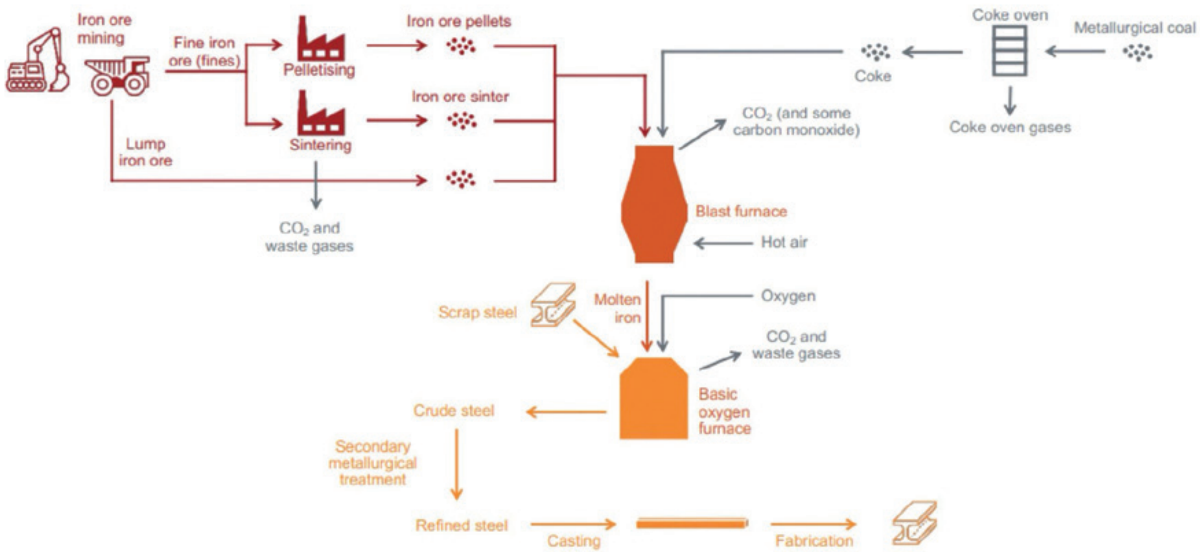
Primary steelmaking has two methods: BOF (Basic Oxygen Furnace or Blast Furnace) and the EAF (Electric Arc Furnace). Global steel production comprises 70% via BOF and 30% via EAF.[205]

The BOF method principally uses iron ore, metallurgical coal and scrap steel to produce steel. On average, this route uses 1,370 kg of iron ore, 780 kg of metallurgical coal, 270 kg of limestone, and 125 kg of recycled steel to produce 1,000 kg of crude steel.[206] During the process, the metallurgical coal acts as the key reducing agent, being heated into coke that reacts with the blast air to produce carbon monoxide that then strips the iron ore of oxygen to produce molten iron and carbon dioxide.[207] At high temperatures, oxygen is subsequently blown through the molten iron and scrap steel, reducing the carbon content to less than 2% and consequently increasing its ductility.[208]

The EAF method feeds recycled steel scrap through a high-power electric charge (with temperatures of up to 1800 degrees Celsius) to melt the metal and convert it into steel.[209] The EAF route typically employs a high percentage of recycled scrap (sometimes 100%), in conjunction with direct reduced iron (DRI) or molten iron. On average, the recycled steel-EAF route uses 710kg of recycled steel, 586kg of iron ore, 150kg of metallurgical coal and 88kg of limestone and 2.3GJ of electricity, to produce 1,000kg of crude steel.[210]

Coal can be used to produce DRI, although natural gas is more commonly used. DRI production involves deriving carbon monoxide and hydrogen from coal or natural gas, and using these gases to reduce iron ore to iron metal.[211] Coal is also typically injected into the slag layer that forms on the surface of the molten steel in the EAF, enhancing slag foaming which generates efficiency improvements.[212]

Figure A.1: Integrated steel-making



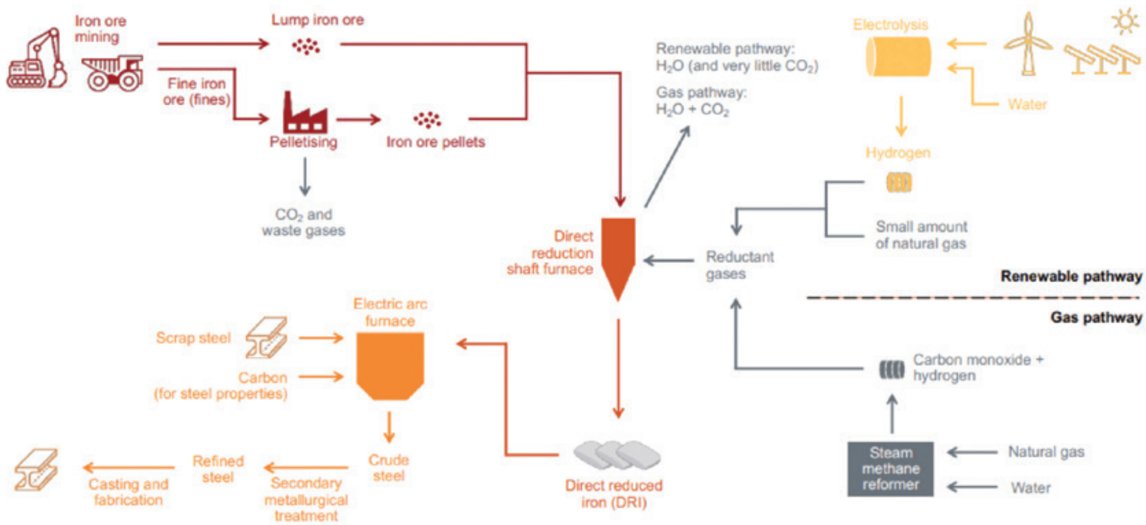
Note: Scrap steel is added to the basic oxygen furnace to control the temperature.
Source: Grattan analysis. Some icons sourced from flaticon.com (2020).

Integrated steel-making process (grattan.edu.au)

Due to the higher use of scrap and lower use of coal, the EAF method is substantially less carbon intensive than BOF. The main sources of emissions in the EAF process is the electricity used to melt the steel, comprising ~67% of emissions. According to some estimates, the carbon emissions for EAF steelmakers is ~25% of their BOF counterparts. While increased production from EAF vis-à-vis BOF steelmakers would reduce emissions, good quality scrap steel is not widely available in the quantities required to make the EAF method the prime source of steel.[213]

Furthermore, it needs to be emphasised that lower-emissions steel is still not 'green steel'. For this, 100% recycled scrap or a carbon-free reductant, in combination power sourced from renewables, is required.

Figure A.2: Direct reduction pathways using either renewable hydrogen or natural gas



Notes: Low-emissions pathways also require that low-emissions electricity be used in each step. Gasified coal can be used in place of natural gas.
Source: Grattan analysis. Some icons sourced from flaticon.com (2020).

Direct reduction pathways using clean hydrogen or natural gas (grattan.edu.au)

HYDROGEN-BASED STEELMAKING

Green steel can be produced by replacing the use of natural gas or coal in the direct reduction process with clean H2. It can also be produced when 100% renewable power is used in conjunction with 100% scrap steel via the EAF route. But because steel products have long lifespans and demand continues to grow, this latter method is not likely to be a major source of green steel.

Therefore, the future of green steel is inextricably linked with commercial clean H_2. The commercial threshold of clean H_2 needs to be met to further the progress of commercially available green steel.

There are two different approaches to hydrogen-based steelmaking[214]:

1. Replacement of "Front End" (blast furnace) with alternative hydrogen-based technology. Typically, this is an H_2 based direct reduced iron (DRI) furnace to produce pig iron followed by an electric arc furnace (EAF) for steelmaking.
2. Incremental: ThyssenKrupp is implementing hydrogen injection in existing blast furnaces.[215] This could deliver up to 20% reduction in CO_2 emissions from the steelmaking process if implemented across all the company's facilities.[216] The capital cost should be much lower with positive impact on CO_2 emissions, sooner, as long as the hydrogen is clean.

GREEN STEEL EXPORT PATHWAYS

Green steel export pathways are inclusive of[217]:

(1) Pathway 1 - Produce steel locally, export semi-finished steel products for overseas fabrication.

(2) Pathway 2 - Produce direct reduced iron locally, export to be refined to steel.

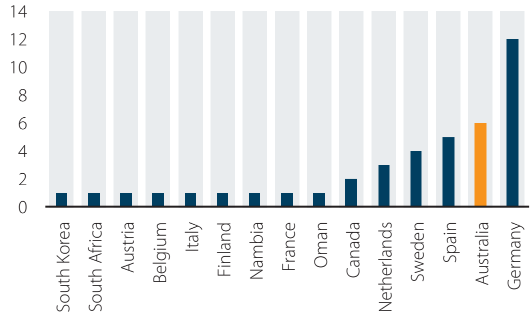
(3) Pathway 3 - Export the ore and hydrogen overseas for steel- making.

It is to be noted that all three pathways require low-emissions electricity in each step.

GREEN STEEL PROJECTS

Europe is leading the way in green steel with several pilot projects underway and major green steel plants already in development. Notably, H2 Green Steel are constructing a facility in Boden, Sweden to produce commercial quantities of green steel by 2025, with a target of five million tonnes per year by 2026.[218] This facility will be the world's first large scale green steel operation. Similarly, ThyssenKrupp are replacing the blast furnace at their Duisburg, Germany site with hydrogen-based DRI technology, intending to produce 2.5 million tonnes of green steel per year by 2026.[219] Seeking solutions to reduce the life cycle emissions associated with their products, automakers such as Volvo and Mercedes-Benz are expected to be key offtakers for the H2 Green Steel and Thyssenkrupp plants respectively.[220]

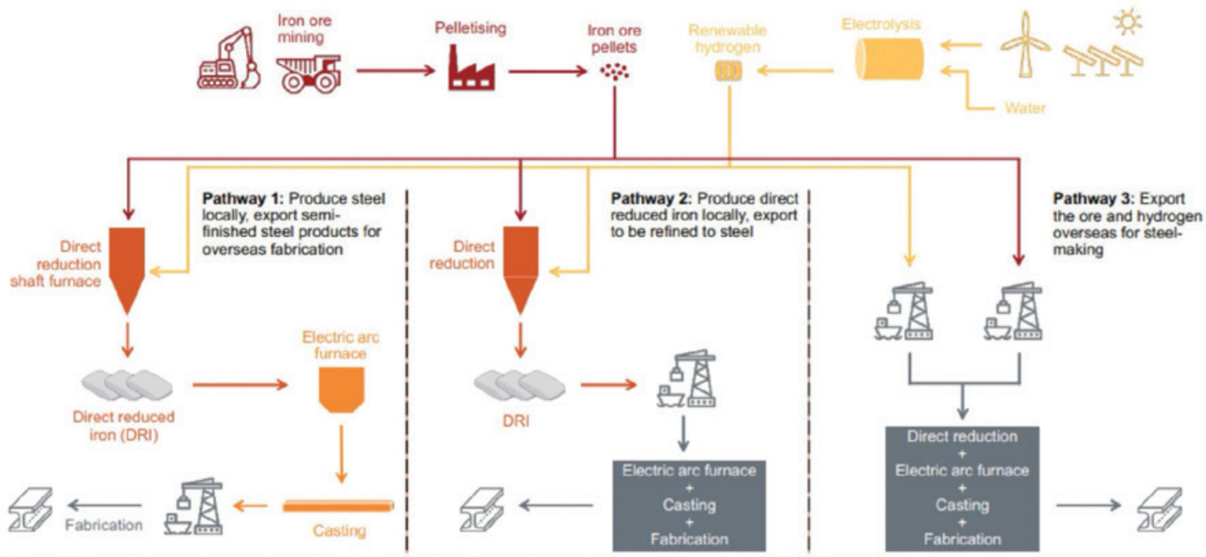
Clean steel projects with green hydrogen component



Source: LeadIT – Green Steel Tracker

This momentum in Europe can be attributed to strong government initiatives, including the European Green Deal which is a set of proposals introduced by the European Council to reduce greenhouse gas emissions by 55% compared to 1990 levels by 2030.[221] Additionally, European countries are often viewed as the best placed to produce green steel due to the prevalence of a carbon price and availability of renewables. However, over the long-term, India and China are expected to have the greatest demand for clean H_2 to use in steelmaking given their existing large production volumes and significant renewables.[222]

Figure 2.3: Green steel export pathways



Notes: All three pathways require low-emissions electricity in each step. Iron ore mining and pelletising need not occur in Australia.
Source: Grattan analysis. Some icons sourced from flaticon.com (2020).

Green steel export pathways (grattan.edu.au)

COMMERCIALISATION TIMELINE

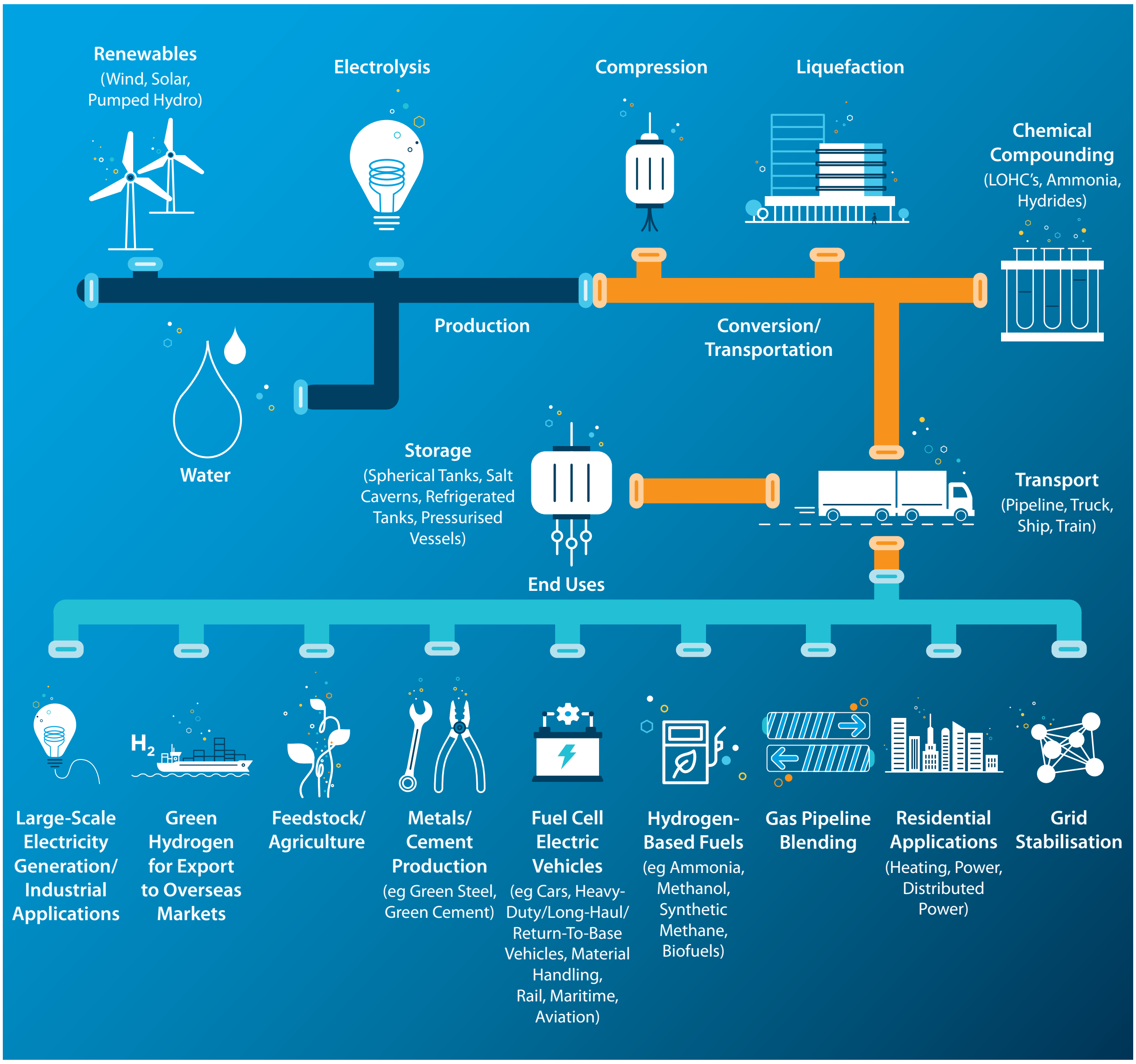
There are two clear pre-requisites for the commencement of commercial green steel - renewable electricity and commercial clean hydrogen.

Renewable electricity is growing in developed economies like Australia. The cost of renewable electricity has decreased to a point where it is now the cheapest source of bulk electricity generation. Given the global focus on H_2 and the requirement to reduce emissions, it would not be surprising for commercialisation of clean hydrogen to occur sooner rather than later. A global price on carbon would also be a significant driver towards clean H_2 and green steel, increasing the relative cost of its non-green equivalents.

Challenges such as technological advancements, economic viability, plant construction and upgrades are the major reasons for the delay in implementation of new technologies in the steelmaking process. EAF steelmaking is the most likely route to lower industry emissions in the medium term, despite implications for scrap steel supply.

Current information suggests it is likely that significant augmentation of electricity and gas networks will be required to make green steel on a viable, commercial basis.[223] Therefore, it is envisaged that green steel will take at least a decade or two to become commonplace in construction. Initial integration of green steel is likely to be led by automakers as steel only comprises a small portion of the sales price for most cars, meaning it can be adopted at a relatively small premium.[224]

THE GREEN HYDROGEN VALUE CHAIN



ELECTROLYSERS

ELECTROLYSERS

A hydrogen electrolyser is a complex piece of equipment which uses an electrical current to convert water molecules (H_2O) into its composite parts – hydrogen (H_2) and oxygen (O_2). The oxygen is returned to the air and the hydrogen is stored in pipeline assets for use. When the electrical energy comes from a renewable source, the hydrogen has no carbon footprint and is considered green or clean hydrogen.

ELECTROLYSERS ENABLE THE USER TO NOT JUST GENERATE HYDROGEN, BUT TO ALSO MANAGE THE LOAD PLACED ON THE GRID.

Electrolysers enable the user to not just generate hydrogen, but to also manage/balance the load placed on the grid - essential to power and energy companies who need the intermittent renewable energy supply to match spikes in consumer demand.

In 2023, green hydrogen constituted around 1%[225] of global hydrogen production. However, Goldman Sachs estimates green hydrogen to supply up to 25% of the world's energy needs by 2050, which would make it a EUR€10 trillion market globally.[226]

According to the IEA, global hydrogen electrolyser capacity was almost 11GW in 2022[227], compared to 0.3GW in 2020.[228] If all projects currently in the pipeline are realised, electrolyser capacity would reach 170-365GW by 2030.

Production of electrolysers has ramped up significantly to meet the global demand for green hydrogen, albeit the growth rate slowed slightly in 2022. Electrolysers will play a central role in the further development and completion of the energy system transition.

TECHNOLOGIES

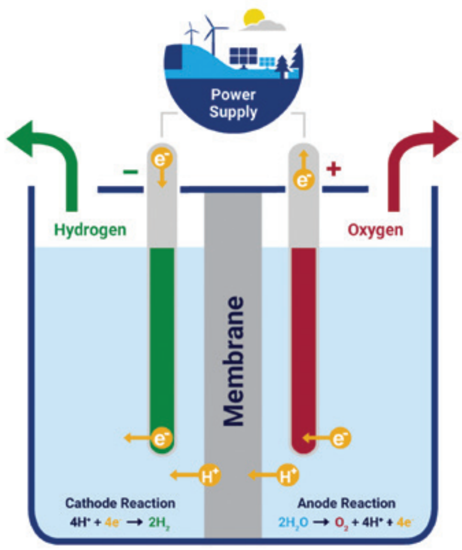
There are different types of electrolysers that support a wide range of solutions based on cost, capacity and application. The two main types include alkaline and PEM technologies.

ALKALINE

Alkaline electrolysers are the most commonly used hydrogen generators in the industry. In alkaline technology, the water is split into its constituents in the presence of a caustic electrolyte solution — frequently potassium hydroxide (KOH).[229]

A reaction occurs between two electrodes (cathode and anode) in the solution composed of water and caustic electrolyte. And when sufficient voltage is applied, water molecules take electrons to make OH^- ions and a hydrogen molecule. The OH^- ions travel through the solution toward the anode, where they combine and give up their extra electrons to make water, hydrogen, and oxygen.

Recombination of hydrogen and oxygen at this stage is prevented by means of an ion- exchange membrane. This was historically made of porous white asbestos, however recent technologies have developed membranes of highly resistant, inorganic materials (asbestos free to eliminate toxicity). The electrolyte remains in the system owing to a closed-loop, pump-free recirculation process.[230]

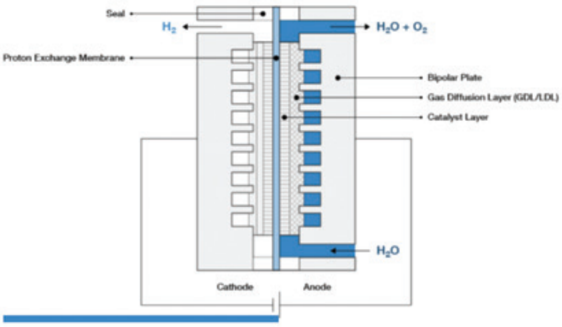


Alkaline electrolysis (Cummins.com)

PEM

Polymer Electrolyte Membrane (PEM) technology is the electrolysis of water in a cell equipped with a solid polymer electrolyte (SPE) to separate hydrogen and oxygen. PEM electrolysis creates a reaction using an ionically conductive solid polymer, rather than a liquid. When voltage is applied between two electrodes, negatively charged oxygen in the water molecules produces protons, electrons, and oxygen at the anode.

The H+ ions travel through polymer membrane towards the cathode, where they take an electron and combine to make hydrogen. The electrolyte and two electrodes are sandwiched between two bipolar plates, which transport water towards them/gases away from them, conduct electricity, and circulate a coolant fluid to cool down the process.[231]



PEM electrolysis (Cummins.com)

OTHER

Other emerging hydrogen electrolysis technologies, include anion exchange membrane (AEM), solid-oxide electrolyser cell (SOEC), protonic ceramic electrochemical cell (PCEC) and photoelectrochemical (PEC) water splitting.

COMPARISONS

Alkaline electrolysis is the more established technology and typically more affordable, as PEM electrolysers involve an acidic environment which require precious metals for the catalyst (as opposed to alkaline being able to use stainless steel and nickel). However, PEMs are often seen as a safer option since the membrane provides a physical barrier between the produced H_2 and O2.

PEM systems also overcome some of the fundamental limitations of traditional alkaline electrolysis in which it is more difficult to pressurise, and additional compression steps are required. Further, PEM is also a more compact machine which is better suited with renewables as they can operate dynamically using varying loads of electricity, allowing PEM electrolysers to be operated when renewable energy generation is cheapest.

SIZES

A typical required flow of hydrogen, and subsequently the size range that current technologies allow for in an individual electrolyser, varies between 0.25Nm^3/h (≈0.00125MW) in small scale generators and up to 4000Nm^3/h (≈20MW) in large scale plants for industrial applications.

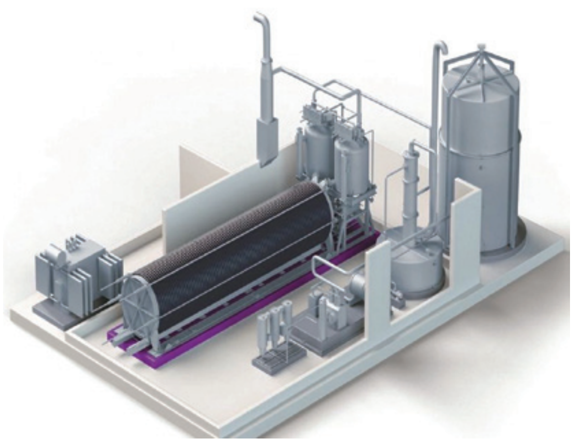
The world's largest electrolyser in operation today is a 150MW alkaline unit in China's Ningxia region by Ningzia Baofeng Energy Group, it is also the largest green hydrogen plant at present. The Baofeng plant is powered by a 200MW solar plant. However, competitors remain ambitious with their plans and Baofeng is unlikely to hold this record for long with several other competitors already in production.

Physical size dimensions can vary greatly, with an average of around ≈12x3x4m for containerised electrolysers, to ≈0.8x1x1.1m for compact scale hydrogen plants with minimal maintenance electrolyser technologies[232].

PRICES

The overall cost comprises the cost of the electrolyser, maintenance and replacement of worn-out membranes, the price of the electricity used for the process, and any subsequent costs for drying, purification, liquefaction, transport and compression of the gas.[233] The balance of plant/ storage is also a significant cost. Additionally, in many cases, including off grid, the renewables and transmission are part of the project directly and not just an operating cost for electricity.

Furthermore, production costs are also highly dependent on factors such as electricity taxes, grid fees and the capacity utilisation rates of electrolysers, which vary widely per region. The two main factors determining the cost of hydrogen production from electrolysis are the cost of electricity and the cost of electrolysers.



Hydrogen electrolyser sample diagram (rechargenews.com)

COST OF ELECTRICITY

Typical up-front capital costs for utility-scale solar PV installations fell by 85% between 2010 to 2020 and by 56% for onshore wind generators. This means lower average costs of generating electricity over the lifetime of assets, which is expected to continue as the energy transition endures. While 2022 saw supply chain issues impacting costs coming down further, the cost of electricity from solar PV still fell by 2% on annual global basis and onshore wind fell 5%.[234]

In the post-COVID era, levelised cost of electricity (LCOE) (measure of average electricity generation costs over the lifetime of a generating plant) has risen because of factors including freight and commodity costs. While that has now largely eased, the costs to finance have increased due to rising interest rates. The International Energy Agency (IEA) expect, in 2024, that the LCOE for onshore wind and solar PV will decline but remain above 2020 rates by 10-15%.[235] (Large scale solar PV installations costs in 2020 were A$41-77/MWh internationally.[236] The equivalent numbers for onshore wind were A$56-93/MWh.[237])

It is also important to note that for an electrolyser to operate at its highest capital efficiency, this will require the input of firm renewable energy to mitigate the risk of unpredictable H_2 production volumes impacted by variables such as weather.

COST OF ELECTROLYSERS

Electrolyser capital costs vary, however they have fallen from around A$3,700 per kW in 2020 to A$2,700 per kW in 2022. The CSIRO estimates costs will fall to around A$200 – A$800 per kW in 2050.[238] This is an average cost as alkaline costs are less than that of PEM electrolysers.

At present, it is believed that Chinese electrolyser manufacturers can produce and sell alkaline technology at well below the price of European competitors because of economies of scale. Further, the electrolyser industry has continuously dropped its capital costs, driven mainly by market need for larger systems and innovation in system design and manufacturing. Costs of hydrogen electrolysis capex is expected to drop further in the next decade, as national targets and pilot projects produce enough volume to realise substantial declines.

In 2021, Siemens Energy announced plans to produce green hydrogen at US$1.50/kg (≈A$2/kg) by 2025 “based on large-scale commercial projects in operation”.[239] This target is in line with the Australian Government’s target of A$2/kg to be competitive with non-renewable energy sources.[240] Currently, the projects are based on wind energy, with underlining assumptions of a cost of electricity at A$16/MWh through a 100MW PEM electrolyser, running a 16.4hrs/day on average.

Australia is well placed to achieve low-cost green hydrogen production due to its low-cost renewable energy supply and the potential to achieve large economies of scale. However, demand needs to be created to drive down costs, and a wide range of delivery infrastructure needs to be built, with the support of government targets and subsidies, to help achieve these future cost targets.

CHALLENGES

Challenges primarily related to green hydrogen electrolysis

MATURITY

Although electrolysis technology has been around for a long time, and is sound and market proven, it is still perceived by some to be new. Hydrogen’s ability to combine with oxygen was actually first noted by Henry Cavendish in 1766, with the first electrolyser subsequently developed in 1800 by Nicholson and Carlisle. However, political, business and consumer comfort with the technology is continuously increasing, and due to the recent increased recognition of green hydrogen as a viable energy source, acceptance of electrolysers is at an all-time high. Both PEM and solid oxide technology is rapidly evolving and it is unclear what is required moving forward as the future scale is unprecedented.

COSTS

Green hydrogen can cost more than double than generating blue hydrogen (SMR with carbon capture and storage), however this is diminishing with rise in demand; in no industry has green hydrogen been found to be cheaper than grey hydrogen.[241]

Manufacturers are working hard to reduce the costs of components within electrolysers, by using product standardisation and repeat parts. Manufacturers are looking at how to improve gigawatt scale in a number of ways. Other major areas of development include membrane-coating techniques/simplifying membrane fabrication; optimising the porous transport layer; and reducing precious-metals content (which account for roughly 30-40% of total cost).

GEOGRAPHY

For consumers in areas that require hydrogen to be transported via methods such as tube trailers, liquefied tank trucks, or transported overseas in hydrogen carrier vessels, this can be a very inefficient and CO_2 intensive process. Since hydrogen is such a light molecule, transportation is constrained in terms of the amount of hydrogen a vessel can hold (whether liquefied or compressed). Furthermore, considerable losses can occur in the storage of hydrogen as a liquid.

Transport costs vary greatly depending on the method used and can prove to be a costly part of the hydrogen value chain. However, pricing outlooks show a rapid decline as the industry develops and demand increases.

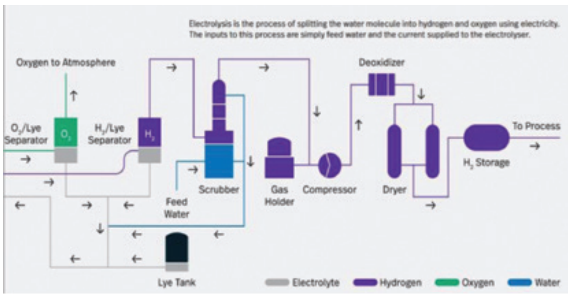
Further, electrolysers provide more efficiency at a lower cost than transporting hydrogen or buying an SMR unit, thus making on-site generation of hydrogen vastly attractive and more economically viable for many hydrogen consumers.

INPUTS

Hydrogen electrolysis specifically requires de-ionised water to be used as an input to production, however feedwater quality is currently an emerging area of research from manufacturers. Early-stage projects are investigating the ability to use dirty water or salt water as an input, as opposed to requiring high-purity water for electrolysis. The cost of this input can be significant and therefore is an important factor to consider. Water temperature must also be kept between 5°C to 40°C.

POST-PROCESSING

Although electrolysers have made strides in efficiency and cost, the produced hydrogen still often requires post-processing steps, such as compression, dehydration or purification. This is predominantly found within alkaline technology as a Potassium Hydroxide solution is used as a process fluid, and therefore traces may need to be removed from the produced hydrogen.



Post-processing of hydrogen from electrolysis (nelhydrogen.com)

TESTING

Safety, purity, flow and reliability are important factors in hydrogen electrolyser manufacturing. Systems must be designed and delivered in an automated manner to produce high purity hydrogen, with strict safety design standards that must conform to the country of installation. Therefore, testing is of importance before transport for packing and shipping to customers, and service departments test each unit according to certain procedures (including pressure, flow, purity, alarms, visualisation and calibrations of sensors). There is also a two-day FAT (factory acceptance test) procedure which in some cases can be witnessed by customers and provides certainty of functioning ability of the electrolyser.[242]

JURISDICTIONS

China has remained the leader of the global markets for several years for both current and pipeline electrolysers with 40% of the global share.[243] However, many European-based companies are also leading the way on developing innovative technologies that better suit the production of green hydrogen through renewable energy. With the announcement from EU executives wanting at least 40GW of electrolysers installed in the EU by 2030 (producing up to 10 million tonnes of renewable hydrogen)[244],this outlook shows continued promising growth for the jurisdiction.

Globally, many organisations are developing sustainability and energy initiatives centred around hydrogen, including projects in the U.S., Canada, Saudi Arabia, Denmark, Austria, New Zealand, Australia, Singapore, Germany, Chile, Spain, China, Portugal and Japan.

ENVIRONMENTAL AND SOCIAL

As the industry rapidly evolves and grows, there are key environmental and social factors which need to be considered. Modern slavery in the supply chain must be consistently scrutinised as the cross-border nature of the industry means it may be difficult to regulate. Mining and processing of raw materials required for use in hydrogen technologies are also higher risk activities. There are large land requirements which require sizable stakeholder engagement as the impact on the wider environment and community may be impacted. The process of electrolysis can be energy intensive, with high demand for water and power usage. The competition for these resources must also be considered, particularly where these resources may be scarce.

USES VS SUPPLY

Development of uses and supply of hydrogen are occurring simultaneously, facing a 'chicken and the egg' scenario. Demand for hydrogen relies on availability and costs, and without demand, supply infrastructure is difficult to justify. As demand for hydrogen increases, the supply infrastructure will be built as cost declines, leaving the question of which comes first. The industry and regulators must consider how to put long term offtake agreements in place to help foster expansion within the industry and allow projects to continue being developed while these two aspects continue to become established concurrently.

HYDROGEN TRANSPORTATION

HYDROGEN TRANSPORTATION

While hydrogen transportation and mobility are divergent topics, this paper explores the feasibility, economics and viability of both industries, and their contribution to the full hydrogen value chain.

Visions of a hydrogen economy often imagine networks of pipes, trucks and ships transporting clean energy in the same way that natural gas is transported. But moving H_2 is costly and its low density presents challenges, even when advanced technologies become fully mature.

Understanding the economic practicalities of H_2 transport is important to be able to compare the cost of producing hydrogen on-site versus the combined cost of production and transportation, especially as the volume, investments and demand for hydrogen rise into the future.

The proximity of Australia to the Asia Pacific region provides a key advantage for supplying Asian markets with H_2, as other potential competitors could be disadvantaged by additional transport costs. Furthermore, Australia can capitalise on its proven track record in energy exports such as LNG, especially to comparatively resource-constrained countries.

Currently, there are relatively established production, transport, and storage technologies for H_2. However, these technologies are yet to be tested at major commercial scale as part of a viable global supply chain. There will be need for further technological development, government policy support and potentially the build out of new supportive infrastructure to push H_2 into full commercial scale development.

CONVERSION

Hydrogen is a very light gas, and contains the highest amount of energy per unit of weight (142MJ/kg) of any substance on earth, apart from nuclear fuels and anti- matter. However, the low density of hydrogen gas by volume (0.08kg/m3) poses significant transportation challenges both domestically and internationally.

The lower the volumetric density, the more space H_2 will require for storage and transport. Therefore, H_2 is generally required to be converted into an alternate state to be moved efficiently. Hydrogen conversion can be achieved in predominantly three ways:

1. Compression
2. Liquefaction
3. Chemical compounding
   - With other molecules to form liquid organic hydrogen carriers (LOHCs)
   - With nitrogen to form ammonia (NH3)
   - With metallic substances to form hydrides*

*Hydrides have a high density however are too heavy and commercially immature to be practical for transport in volumes above a few kilograms, therefore are not investigated further within this paper.

Any conversion treatment could considerably add to the cost of H_2, potentially becoming the second largest price component in a project. As a result, transport cost estimates include the cost of transport, conversion/re-conversion of H_2 in a gas-to-gas state, and storage. Most hydrogen is currently used directly worldwide, with only a small proportion converted/transported to end- users due to such high associated costs.

Each conversion alternative has advantages and disadvantages, with the most economically viable choice dependent on the geography, distance, scale and required end use.[245]

COMPRESSION

The compression of H_2 can make a large difference in increasing its density in gaseous form, and ultimately reducing the space required for its transportation.

Hydrogen in its gaseous state is at an atmospheric level of ~1 bar, with compressed H_2 between 350-750 bar. Applying to what is required in various transportation methods, a pressure of around 70 bar is needed in transmission pipelines, and 1000 bar in storage tanks.[246]

Compression can be achieved in three ways:

- Using a standard separate compressor machine
- Changing the operating pressure of an electrolyser (for green H_2)
- Using a separate electrochemical device

There is a plethora of different compressor machine types with the most common being reciprocating, rotary, ionic and centrifugal compressors. Pressurisation is generally caused by the back and forth movement of a piston or diaphragm via a linear motor, or rotation through a turbine at high-speed.

Combining the production and compression of H_2 in the electrolyser, however, is an attractive option from the perspective of equipment count and process complexity. The downsides include the design of the electrolyser struggling to withstand higher pressures and the potential increase in gas permeation through the membrane affecting both cost and efficiency/durability.[247] Higher electrolyser pressures increase permeation losses, which means more hydrogen ends up on the oxygen side rather than on the product side, translating to a higher energy consumption and safety risk for the anode.

Hydrogen compressor machine (neuman-esser.de)

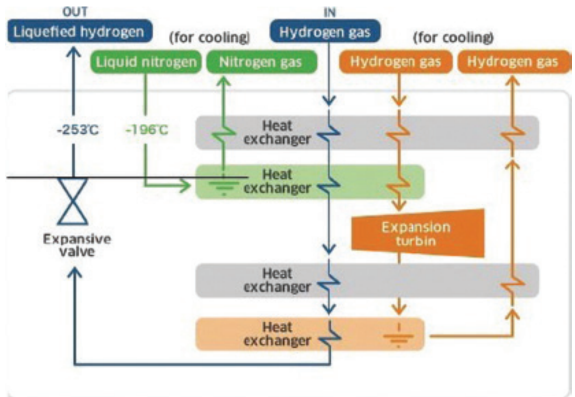
Electrochemical compressors can also be used via PEM technology to drive the dissociation of H_2 at the anode, and its recombination at higher pressures at the cathode.

This issue of permeation losses is also faced within compressed H_2 tube trailers. Due to their still comparatively quite low volumetric energy density, trailers are only commercially available for small distances and for capacities of a maximum amount of 300kg.[248] This highly limits the viability of compressed H_2 being utilised in road transport.

The cost of compression is relatively small compared to overall production costs. It is generally the cheapest conversion treatment, however is the least dense by volume. Based on 2020 projections, compression adds an average of A$0.9/kg to the cost. By comparison, LOHC adds A$1.7/kg, ammonia adds A$2.6/kg, and liquefaction adds A$4.1/kg.

LIQUEFACTION

Hydrogen liquefaction is one of the most common and significant processes in H_2 transportation and storage. As hydrogen is not dense enough for long- distance transport to be commercially viable, producers utilise liquefaction by way of cooling H_2 to its very low boiling point. Liquid nitrogen is used in the process to pre-cool before it can be chilled further to the temperature of -253°C.



The hydrogen liquefaction procedure (global.kawasaki.com)

Hydrogen liquefaction is complex and energy intensive relative to other bulk gases. Liquefaction requires the input of liquid nitrogen and a significant amount of electrical energy (about 11–15kWh/kg H_2), which is equal to or greater than one-third of the chemical energy of hydrogen (33kWh). If the H_2 itself were to be used to provide this energy to cool, then it would consume between ~25-35% of the initial quantity of hydrogen.[249] This is considerably more energy than is required for LNG, which consumes around 10%. The liquefaction process itself is carried out within a highly insulated cold box cylinder, in which heat exchangers and expansion turbines featuring high-speed rotation achieve a highly purified liquid gas.[250]

Liquefaction is the most expensive method at an average of adding A$4.1/kg to the levelised cost of hydrogen. Liquefaction can also run the risk of boil-off meaning facilities are best located at H_2 export hubs. Liquefaction potentially requires reconversion back to its gaseous state dependent on end use, which can again result in energy losses. This is captured into the cost of the conversion treatment.

Linde's hydrogen liquefaction plant (fuelcellworks.com)

LOHCS

Hydrogen can also be converted into other chemical compounds, such as with liquid organic hydrogen carriers (LOHCs). These can then be stored or transported via dedicated pipelines or trailers.

Perhydro-dibenzyltoluene (PDBT) and methylcyclohexane (MCH) are the most well investigated LOHCs.[251] PDBT has a volumetric hydrogen storage density of 57kg/m3, and MCH has 47kg/m3.

Making LOHCs involves storing H_2 in a chemical bonded form through reversible, catalytic hydrogenation.[32] For reconversion at delivery, a H_2 release unit (i.e. chemical reactor for dehydrogenation) is also required. The major advantage of LOHCs is its ability to be stored safely at ambient conditions, where neither high pressures nor low temperatures are needed. This is in addition to the relative purity of H_2 after reconversion, and its transportation abilities without the need for cooling. Their properties are similar to crude oil-based liquids (e.g. diesel or gasoline), therefore a mature supply chain already exists for their handling, storage and transport.

Chemical liquid carriers enable less complex storage engineering. However, additional consideration for the end-user should be taken, due to needing the necessary facilities to be able to remove the liquid chemical carrier. This process would require the energy equivalent of 35-40% of the H_2 itself.[30] In addition, the carrier molecules in an LOHC are often expensive and not used up when the H_2 is created again at the end of the process. Therefore causing the need for it to be shipped back to their place of origin either via truck or parallel pipeline operating in the opposite direction.

The main differences in kinds of LOHCs include prices of carrier molecules, and toxicity levels. Methanol and formic acid are other alternatives, however they do lead to GHG emissions if used directly. The cost of LOHC conversion adds about A$1.7/kg to the levelised cost of H_2 itself. However, effective utilisation of the heat released in the conversion process could increase the efficiency of the value chain and reduce the overall price.

AMMONIA

There is particular interest in ammonia as an early pathway, as it allows for easy handling in shipping due to its high energy density (123kg/m^3 at 10 bar pressure) compared to liquid hydrogen (70kg/m^3 at 1 bar).

Ammonia is the second most widely used inorganic bulk chemical in the world (commonly used for feedstock), and already has a mature and efficient supply chain. The ability to use existing infrastructure for its transport and distribution enables a reduction in the cost of reaching final users. However, because of its toxicity it requires handling by certified personnel only, possibly restricting its techno- economic potential.[32] There is also a risk that some non- combusted ammonia could escape, which can lead to the formation of particulate matter (an air pollutant) and acidification. However, if ammonia is the end use and there is no further need for re-conversion, it would be more efficient to transport ammonia in that form (e.g. Ammonia for co-firing in coal power stations in Japan).

As with the LOHC process, ammonia's ease of handling will need to be balanced against the associated energy output for the initial conversion of H_2 to ammonia, and the subsequent reconversion for end-use. This process may see cost reductions as technological developments are introduced to the market, (e.g. the CSIRO's development of an ammonia conversion technology at point of use through vanadium membranes), however current prices reflect a lack of competitiveness. The NEOM Green Hydrogen Project that is being constructed in Saudi Arabi is due to open in 2026. Its ambition is to produce up to 600 tonnes of green hydrogen in the form of green ammonia per day as a cost-effective way to export hydrogen globally.[252]

Producing ammonia is typically obtained on a large-scale by the Haber-Bosch process which combines H_2 and nitrogen together directly through synthesis.[32] Ammonia is naturally a gas at normal temperature and pressure, but can be liquefied at 10 bar or - 33°C, which would hold a 50% higher volumetric energy density than liquid H_2. Much of the electricity used to convert H_2 into fuels and feedstocks is lost during the process of conversion (7-18% of the energy contained in the H_2) with similar levels lost in re-conversion.

The main cost components for the production of ammonia are outside the H_2 production itself (including capex around the electrolyser and electricity costs). However, in terms of the cost of conversion, this adds ~A$2.6/kg to the levelised cost of H_2.

TRANSPORTATION

Depending on how hydrogen is converted, different modes of transport become available. The four most common methods are inclusive of pipeline, truck, ship and train.

It is also noted that storage costs are incorporated within the levelised cost of transport in each of the segments outline in the table. It is assumed that pipelines store H_2 in salt caverns, liquid hydrogen in large spherical tanks, ammonia in large refrigerated tanks, and compressed H_2 in pressurised vessels.

Cost of transportation methods

Transport Method	CAPEX (A$)	Cost (A$/ kgH2/50km)
Pipeline	$1.03-1.55M/km	+$0.1-0.3
Truck	CGH2: $0.96M LH2: $1.39M	CGH2: +$1.05 LH2: +$5.95
Ship	$310-533M	NH3: +$0.02 LH2: +$0.05

PIPELINE

Hydrogen can be transported in pipelines in two ways:

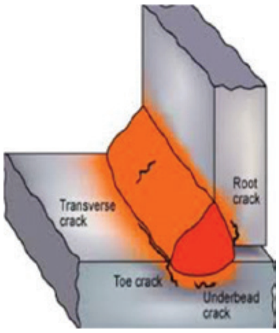
1. Blended into existing natural gas pipelines.
2. Building new specialised H_2 pipelines.

Pipelines are the cheapest way of transporting large volumes of H_2 over long distances on land. Transmission is facilitated from high pressure gaseous pipelines in production/storage facilities, to a low-pressure distribution system that would deliver H_2 to end-users. Pipelines have low operational costs and lifetimes of between 40-80 years. However, their two main drawbacks are the high capital costs entailed and the need to acquire rights of way (RoW).[253] These mean that the certainty of future H_2 demand and government support are essential if new pipelines are to be built.

Blending into Existing Gas Network

Blending clean H_2 into existing natural gas systems could help partially decarbonise gas networks, with a number of operational or demonstration projects already underway in Australia (including the HyP SA blended-H_2 project) to examine the potential.

Metering, valves, some iron/steel pipes and storage facilities have limitations on the amount of H_2 that can be blended due to the leaking of H_2 through joints and embrittlement to some alloys of steel.[254] This refers to the small size of the H_2 molecules which can infiltrate steel molecules, react with the carbon steel and cause cracking/material failure. The higher the carbon content, pressure and H_2 concentration, the higher the chances of embrittlement.



Types of cracking in steel from hydrogen embrittlement (twi-global.co)

Upgrades (at various costs) will be required to blend H_2 at higher concentrations. H_2 pipelines made of polyethylene (HDPE pipe) and other fibre-reinforced polymers/plastics are not susceptible to these problems and are therefore fit for blended or pure H_2 distribution.[34] HDPE pipes are commonly found in Australian gas distribution networks, and it has been asserted that Australia's existing gas infrastructure is capable of being utilised for the transport and storage of volumes of hydrogen through blending up to 10%.[255] However, innovation continues to push the boundaries in the gas pipeline conversions space. In 2023, APA Group, one of the largest owners of gas pipelines in Australia, announced the successful completion of their laboratory testing into potentially transporting up to 100% hydrogen through a 43km section of the Parmelia gas pipeline in WA.[256]

Another alternative is to line steel pipelines with internal plastic coating, or the conversion into ammonia which avoids embrittlement. However, this is somewhat limited by concerns that higher percentages of H_2 could impact residential/commercial consumer appliances, industrial user plant and equipment, and potentially degrade the existing network infrastructure due to cracking.

Keeping track of how much H_2 has been injected into the grid and its carbon intensity is an important method of accounting and is called a "guarantee of origin".[257] This is essential if operators are to be paid a premium for supplying lower-carbon gas.

Hydrogen blending into the natural gas stream could be used to provide a pure stream of H_2 if separated at the end-use site. There are several options to do this, including pressure swing absorption, however this is currently a relatively expensive process.

New Hydrogen Pipelines

For higher H_2 percentages, or pure H_2 gas, new pipelines/ mains/meters/appliance replacements would be required. HDPE pipe has already begun being installed in Australia through replacement programs.[258] Pending further testing, HDPE pipe could also be deemed as suitable for 100% H_2 presenting an opportunity to replace existing distribution networks within the country.

Another challenge faced in pipeline usage is that three times more volume (and therefore a 2-20% larger pipeline diameter) is needed to supply the same amount of energy as natural gas.[60] Additional transmission and storage capacity across the network might therefore also be required, depending on the extent of growth in demand for H_2.

Costs

Overall, the levelised cost of transporting H_2 via pipeline over a distance of 50km is around A$0.1-0.3/kg$H_2$. It is estimated that this cost could also fall as low as A$0.06-0.2/kg$H_2$ if HDPE pipe is used and storage costs reach their lowest potential. The upper end of this price scale arises from the need for and operational costs of injection stations on the transmission and distribution grids to maintain pressure.

However, these figures do not consider the upfront capex required to upgrade/build pipelines for transmission – this cost is subjective to country-specific regulations and existing infrastructure. RoWs also need to be acquired from landowners in the case of new pipelines, which are estimated to account for 7-9% of such capex.[259]

Overall, pipeline transmission is generally the cheapest option for H_2 transportation in distances of less than ~1,500km. Trucks are more suitable for short distances of low volume, and shipping becomes more economically viable for voyages of above 5,000km.

TRUCKS

Trucks are already regularly used to transport hydrogen in any state and although this method of transport is more expensive than pipelines, their versatility makes them useful in places with low H_2 demand, for short distances, or for deliveries of smaller volumes to dispersed users.

The two leading modes of H_2 truck transport include compressed gas (CGH_2) trailers, or in liquid hydrogen tankers (LH_2). LOHC and ammonia are cheaper alternatives, however their immature commercialisation in road transport, in conjunction with levels of toxicity, outweigh cost savings for truck distribution.

Truck with a compressed hydrogen tube trailer

Truck with a liquid hydrogen trailer

CGH_2 vs LH_2 trailer types (energy.gov)

CGH_2 trucks are the most common method and can carry pressurised H_2 in either long horizontal tubes, or in vertical containers. Once the truck has reached its destination, empty containers can either be refilled or exchanged for full ones.

For CGH_2, a single trailer can only hold up to 1,100kgH_2 (at 500 bar) in lightweight composite cylinders giving it the lowest H_2 carrying capacity of all trailer technologies. Even this weight is rarely achieved in practice due to safety regulations limiting the allowable pressure/ dimension/ weight of the tubes.

LH_2 cryogenic tanker trucks can carry up to 4000kgH_2 and are commonly used today for journeys of up to 4000km. They are unsuitable for any greater distances as the H_2 heats up and causes a rise in pressure, and are comparatively quite expensive due to the energy intensity required to maintain the highly-insulated vehicle.

Costs

CGH_2 trailer capex translates to around A$776,700 for a standard capacity of 700kg/H_2. The additional cost of a diesel- powered tractor unit to tow the trailer is around A$182,650, bringing the total amount to ~A$960,000.

Comparing this to an insulated LH_2 cryogenic trailer, capex is around A$1,206,800 for a capacity of 4,400kg/H_2. With the addition of the tow tractor unit, the total amount is ~A$1,390,000.

Due to the high cost of liquefaction compared to compression, LH_2 trucking is more expensive for shorter distances. However, because a LH_2 trucks fits 5-12x more H_2 than CGH_2 in terms of density, the unit cost of transport becomes significantly lower. As a result, at distances greater than 350km, LH_2 trucks start to outcompete CGH_2.

Overall, for trips of 50km the levelised cost of transporting via truck ranges between A$1.05-5.95/kg$H_2$, depending on the trailer.

Cost comparisons across trailer types

Type	Truck Cost (A$)	Capacity	OPEX (per 50km)
CGH_2	~$960,000	700kg/H2	$1.05/kg
LH_2	~$1,390,000	4,400kg/H2	$5.95/kg

SHIPS

The export of H_2 is forecast to be a key enabler of a global low-carbon economy. Studies are currently being carried out in Australia, with Kawasaki Heavy Industries' world-first liquid hydrogen carrier vessel, the 'Suiso Frontier', having departed Victoria for Japan in January 2022. This marks the first export cargo of LH_2 globally, putting Australia at the forefront of the energy systems transition.

Shipping tankers could be facilitated using existing or additional infrastructure at ports in Australia that have capabilities in handling gas and liquid petroleum products. These infrastructure requirements include storage tanks, liquefaction, regasification, and conversion plants to be able to facilitate shipping supply chains at loading/receiving terminals as appropriate.

The size of H_2 shipping vessels are much smaller than that of LNG ships due to the designs being in early trial phases and regulation restrictions from the International Maritime Organisation (IMO). The Suiso Frontier has been designed at 116m long, and has a capacity of up to 1,250m^3. [260] The HySTRA consortium plan to scale up capacity after the achievement of successful initial voyages. After the success of the Suiso Frontier in 2022, which achieved a world first in transporting liquefied hydrogen, the next phase of the project is to commercialise liquefied hydrogen carriers by 2030.[261] By comparison, standard ocean LNG vessels are around 350m long, and have holding capacities of up to 260,000m^3. Other main differences between LH_2 and LNG ships include a significant increase in the insulation required for H_2 due to its much lower boiling point, and other safety concerns such as the flammability of liquid pools and potential gas leaks from cracking.

Other H_2 pilot ship projects underway include:

- Korea Shipbuilding & Offshore Engineering (KSOE): Developing a high- strength steel and enhanced insulation commercial liquefied hydrogen carrier to mitigate the risks of pipes/tanks cracking.
- The Wilhelmsen Group: Piloting a "roll- on/roll-off" LH_2 ship by way of containers/trailers being driven onboard (expected to be operational by 2024).
- Ballard Power Systems/GEV: Developing a compressed hydrogen transport ship with a cargo capacity of 2000 tonnes of compressed H_2(23m m^3) (expected by 2025/26).

The Suiso Frontier (hydrogenenergysupplychain.com)

Boil-off is again something to be considered with long duration transport. In LNG vessels, for a 16-day voyage (i.e. Australia to Japan) the ship faces around 0.2-3.2% boil-off per day. Proposed solutions include increased insulation efficiency by adding a vacuum-insulated double- shell (or essentially a tank within a tank to prevent heat transfer). As well as a glass fibre reinforced polymer support structure, and a H_2- compatible gas combustion unit to ensure that any boil-off gas is safely combusted to reduce the risk of increased pressure.

Further challenges faced by ship transportation include the need for contracted commercial and supply chain terms, and because unless a high-value liquid can be transported in the opposite direction in the same vessel, ships would need to return empty. Like that of early LNG product export, long-term offtake contracts with minimum take-or-pay volumes will be required to get investors comfortable that revenues will pay back the substantial upfront capex. Increased carbon taxes, government grants or incentives to absorb H_2 prices could help spur the initial demand required for full-scale commercialisation to take place.

Costs

Costs to ship H_2 can vary due to different conversion requirements and carriers used. H_2 shipping involves high costs of conversion, storage and reconversion, and low unit costs of transport. In other words, once the non- transport components are accounted for, the cost of shipping grows only modestly with distance. As a result, the larger the distance, the more attractive shipping gets relative to other options like pipelines, with ~5,000km being a rough distance starting point for competitiveness.

In terms of ship capex, due to projects being inaugural developments, estimates of the cost of the vessels are difficult to come by. Speculation is that H_2 ships will cost more than LNG vessels (which generally range between A$65-310 million each depending on size). The IEA suggest future specialised H_2 tankers with a capacity of 11,000 tonnes cost up to A$533 million.[262]

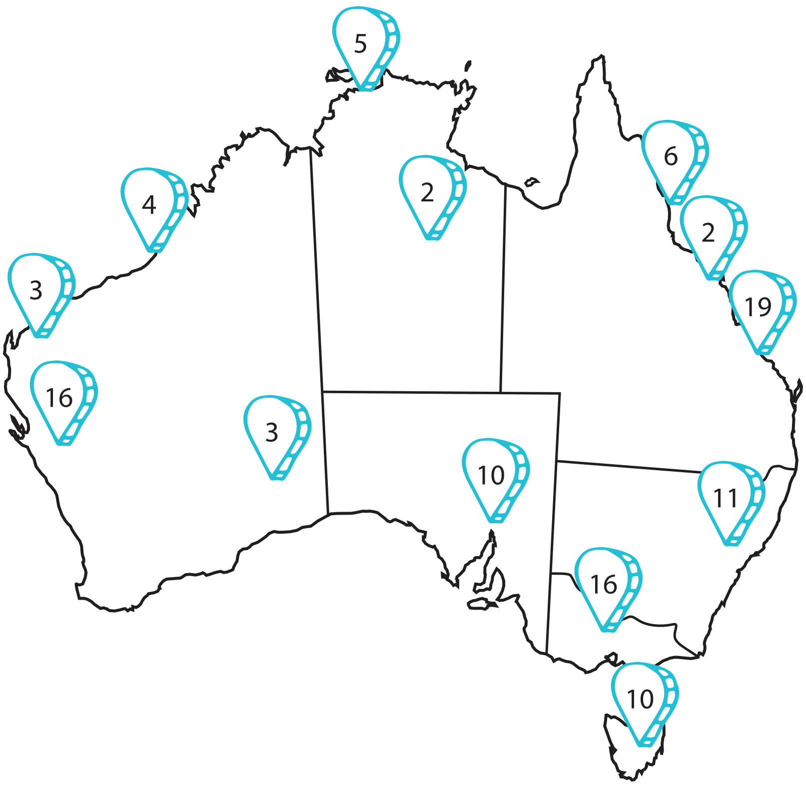
The overall levelised cost of transport associated with LH_2 over a 10,000km voyage, is currently expected to add more than A$10.06/kg$H_2$ (including the use of export/import facilities). Delivery via ammonia is substantially cheaper at around A$4.06/kg$H_2$, due to higher technological/commercial maturity with some existing infrastructure already in place. However, again it must be noted that this cost does not include its re-conversion for end-users which can alter the price competitiveness greatly. Additionally, recent studies by IEA in 2023 shows that the costs of shipping ammonia and LOHCs can be significantly cheaper than shipping LH_2.[263]

OTHER

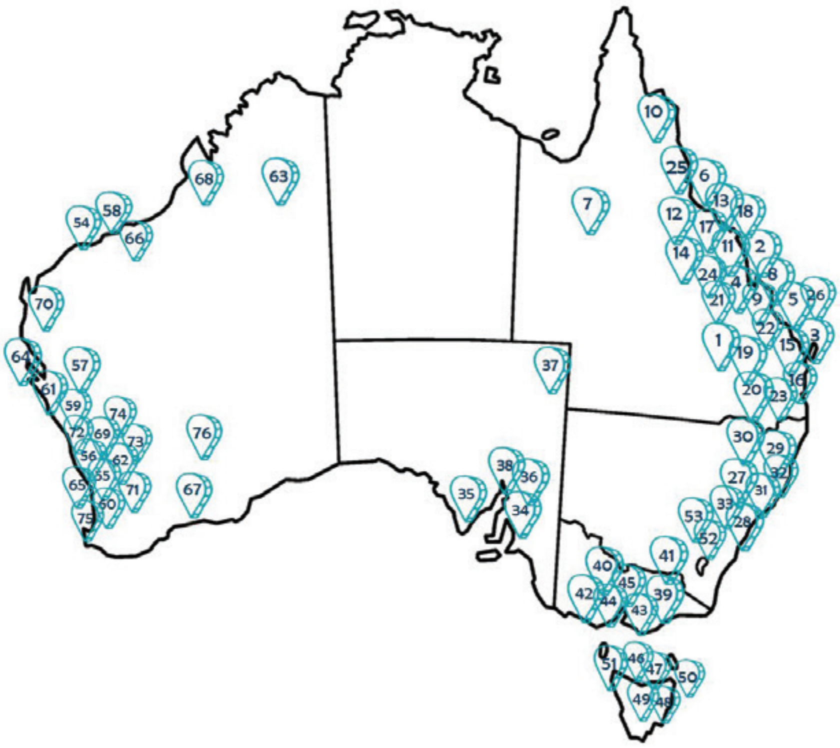
A feasibility study, utilising the Inland Rail Productivity Enhancement Program, is currently being undertaken by the Queensland Hydrogen Industry Cluster (H2Q), and the Queensland Transport and Logistics Council (QTLC).[264] This aims to future proof the infrastructure investment and strategically integrate intermodal facilities into the H_2 supply chain. Although this would generally be a more expensive option than pipeline, rail transport of H_2 has already seen successful demonstration projects across other jurisdictions such as Germany.

AUSTRALIAN HYDROGEN PROJECTS

AUSTRALIAN HYDROGEN PROJECT MAP



2023
107 projects



2021
76 projects

QUEENSLAND

#	Project name	Key Parties	Type of project	Location
#	QLD			
1	Bio-Hydrogen Demonstration Plant	Southern Oil Refining Pty Ltd	Hydrogen from Waste Gases	Yarwun
2	Central Queensland Hydrogen Project	Stanwell Corporation Ltd, Iwatani Corporation, Kawasaki Heavy Industries, Marubeni Corporation, Kansai Electric Power Company, APA Group	Hydrogen	Rockhampton
3	Daintree Microgrid Project	Daintree Renewable Energy Pty Ltd	Hydrogen Storage, Solar Battery	Daintreee Rainforest
4	Edify Green Hydrogen Project	Edify Energy	Hydrogen	Townsville
5	Emerald Coaches Green Hydrogen Mobility Project	Emerald Coaches	Hydrogen Mobility	Emerald
6	Gibson Island Green Ammonia Feasibility	Fortescue Future Industries, Incitec Pivot Ltd	Hydrogen, Green Ammonia	Gibson Island
7	Glencore Surat Hydrogen Project	Glencore	Hydrogen CCS	Wandoan
8	Goondiwindi Hydrogen	Goondiwindi Regional Council, The Hydrogen Collective	Hydrogen Waste Water Treatment	Goondiwindi
9	Green Hydrogen Export Project	Origin Energy, Kawasaki	Green hydrogen	Townsville
10	Green Methanol Feasibility Study	Cement Australia (a Holcim and Heidelberg Materials joint venture), Mitsubishi Gas Chemical Company	Hydrogen, Methanol	Gladstone
11	Renewable Hydrogen Production and Refuelling Project	BOC Limited, ITM Power Pty Ltd, Hyundai Motor Company Australia Pty Ltd	Green Hydrogen, Refuelling Station	Pinkenba
12	H2U Hub Gladstone	H2U	Hydrogen, Ammonia	Gladstone
13	Han-Ho H2 Hub – Feasibility Study	Ark Energy Corporation Pty Ltd	Green Hydrogen, Ammonia	Collinsville
14	Hay Point Hydrogen Project	Dalrymple Bay Infrastructure Ltd, North Queensland Bulk Ports Corporation, Brookfield Group, ITOCHU Corporation	Hydrogen Production, Hydrogen Storage	Hay Point
15	Hydrogen Hubs Powering Remote Communities (H2H)	Ergon Energy Corporation Ltd	Green Hydrogen	North Queensland
16	Hydrogen Mobility Project	Aurizon	Hydrogen Refuelling Station	Townsville
17	Hydrogen Park Gladstone	AGIG	Green Hydrogen	Gladstone
18	Hydrogen Powered Trains Feasibility Study	Aurizon, Anglo American	Hydrogen Fuel Cell	Central & Northern Queensland

	Project name	Key Parties	Type of project	Location
19	Brigalow Peaking Power Plant	Queensland Government (CS Energy as development lead)	Hydrogen, Natural Gas	Chinchilla
20	Kogan Creek Renewable Hydrogen Demonstration Plant	CS Energy	Green Hydrogen, Solar Battery	Chinchilla
21	Origin and ENEOS	Origin Energy, ENEOS	Green Hydrogen	Gladstone
22	Pacific Solar Hydrogen Project	Austrom Hydrogen	Green Hydrogen, Solar Battery	Port of Gladstone
23	Sir Samuel Griffith Centre	Griffith University	Green Hydrogen, Solar Battery	Brisbane
24	Sumitomo Green Hydrogen Production Plant	Sumitomo Corporation, JGC Group	Green Hydrogen	Gladstone
25	SunHQ Hydrogen Park	Ark Energy Corporation	Hydrogen Mobility	Townsville
26	Swanbank Clean Energy Hub	CleanCo	Hydrogen	Swanbank
27	Transdev Mobility Trial	Transdev Queensland	Hydrogen Fuel Cell	Brisbane

Source: CSIRO - HyResource

NEW SOUTH WALES & SOUTH AUSTRALIA

	Project name	Key Parties	Type of project	Location
#	NSW			
28	Good Earth Green Hydrogen and Ammonia Project	Hiringa Energy (Operator), Sundown Pastoral Company	Green Hydrogen, Ammonia	Moree
29	Hunter Energy Hub	AGL Energy, Fortescue Future Industries	Green Hydrogen, Ammonia	Hunter Valley
30	Hunter Hydrogen Hub	Origin Energy, Orica	Hydrogen	Hunter Region
31	Hyundai Integrated Hydrogen Production and Refuelling System	Hyundai Motor Company Australia	Hydrogen Storage, Refuelling Station	Sydney
32	Illawarra Hydrogen Technology Hub	BOC Limited	Hydrogen Mobility	Woollongong
33	Port Kembla Hydrogen Refuelling Facility	Coregas	Refuelling Station, Hydrogen Mobility	Port Kembla
34	ScaleH2	ATCO Australia Pty Ltd	Green Hydrogen, Ammonia	Port Kembla
35	Tallawarra B Dual Fuel Capable Gas/ Hydrogen Power Plant	Energy Australia	Electricity Generation	Illawarra Region
36	Western Sydney Green Gas Project	Jemena	Hydrogen Gas, Grid Generation	Horsley Park
#	SA			
37	Cape Hardy Green Hydrogen Project	Amp Energy, Iron Road Ltd	Hydrogen, Ammonia	Cape Hardy

	Project name	Key Parties	Type of project	Location
38	entX and Kimberly-Clark – Millicent Mill Green Hydrogen Project	entX Limited and Kimberly-Clark Australia	Green Hydrogen	Millicent
39	Eyre Peninsula Gateway Project - Demonstrator Stage	Worley, Hydrogen Utility (H2U)	Green Hydrogen, Ammonia	Eyre Peninsula
40	Green Cement Decarbonisation Project	Hallett Group, Elecseed, Korea Hydro and Nuclear Power Company	Green Hydrogen	Port Augusta
41	Green Hydrogen and Battery Energy Storage System	Marubeni Corporation	Hydrogen Transportation	Adelaide
42	Hydrogen Park SA (HyP SA)	AGIG, Siemens, SA Power Networks, KPMG	Green Hydrogen, Hydrogen Mobility	Tonsley
43	Neoen-ENEOS Export Project	Neoen Australia, ENEOS Corporation	Hydrogen	Goyder Regional Area
44	Port Pirie Green Hydrogen Project	Trafigura Group Pte. Ltd	Green Hydrogen	Port Pirie
45	SM1	Vast	Green Hydrogen, Methanol	Port Augusta
46	South Australian Government Hydrogen Facility	The Office of Hydrogen Power South Australia	Hydrogen	Whyalla
47	Torrens Island Green Hydrogen Hub	AGL Energy Limited (AGL: consortium lead), Osaka Gas Australia, INPEX Corporation, Brickworks, Flinders Ports, Adbri, SK ecoplant, Spark Renewables	Green Hydrogen	Adelaide

Source: CSIRO - HyResource

VICTORIA, TASMANIA AND AUSTRALIAN CAPITAL TERRITORY

	Project name	Key Parties	Type of project	Location
#	VIC			
48	Calix Zero Emissions Steel Technology-pre-FEED and FEED Study	Calix	Green Steel	Bacchus Marsh
49	Development of Altona Renewable Hydrogen Plant	Air Liquide Australia Solutions Pty Ltd	Hydrogen	Melbourne
50	Energys Renewable Hydrogen Production Facility	Energys Australia Pty Ltd	Green Hydrogen, Mobility	Melbourne
51	Geelong Hydrogen Hub	Geelong Port, CAC-H2	Hydrogen, Ammonia	Corio Bay
52	Geelong New Energies Service Station Project	Viva Energy Australia	Green Hydrogen, Mobility	Geelong
53	Hydrogen Energy Supply Chain	Kawasaki Heavy Industries, AGL, J-Power, Iwatani, Marubeni, Sumitomo, Shell	Brown Hydrogen, Hydrogen Export	Latrobe Valley
54	Hydrogen Fuels Australia Truganina HRS	Hydrogen Fuels Australia	Green Hydrogen, Mobility	Truganina
55	Hydrogen Park Murray Valley	AGIG, ENGIE	Green Hydrogen	Wodonga

#	Project name	Key Parties	Type of project	Location
56	Portland Renewable Hydrogen Project	Countrywide Renewable Hydrogen Ltd, Glenelg Shire Council, Port of Portland	Green Hydrogen, Wind, Ammonia	Port of Portland
57	MyHome	Australian Gas Infrastructure Group (AGIG)	Hydrogen Home	Melbourne
58	Liquefied Hydrogen Supply Chain Commercial Demonstration Project	Electric Power Development Co. (J-Power), Sumitomo Corporation, Kawasaki Heavy Industries (KHI), Iwatani Corporation, INPEX Corporation	Hydrogen Export	Gippsland
59	Melbourne Hydrogen Hub	Countrywide Renewable Hydrogen Ltd, Melbourne Market Authority	Green Hydrogen, Solar	Epping
60	Portland Renewable Fuels	HAMR Energy	Hydrogen, Methanol	Portland
61	Renewable Hydrogen Hydro-Gen 1	Yarra Valley Water	Green Hydrogen, Waste	Melbourne
62	CSIRO Hydrogen Refuelling Station	CSIRO, Swinburne University of Technology	Hydrogen Mobility	Clayton
63	Toyota Ecopark Hydrogen Demonstration	Toyota Motor Corporation Australia Limited	Hydrogen Mobility	Altona
64	Warrnambool Hydrogen Mobility Project	Warrnambool Bus Lines	Hydrogen Mobility	Warrnambool
#	**TAS**			
65	ABEL Energy Bell Bay Powerfuels Project	ABEL Energy	Hydrogen, E-Methanol	Bell Bay
66	Fortescue Green Ammonia Plant	Fortescue Metals Group	Green Hydrogen, Ammonia	Bell Bay
67	George Town Project	LINE Hydrogen	Green Hydrogen, Mobility	George Town
68	Grange Resources Study	Grange Resources (Tasmania) Pty Ltd	Hydrogen Gas	Burnie
69	H2Tas Project	Woodside, Marubeni Corporation, IHI Corporation	Green Hydrogen, Ammonia	Bell Bay
70	HIF Carbon Neutral eFuels Manufacturing Facility	HIF Global	Green Hydrogen, eFuel	Burnie
71	Hydrogen Brighton Project	Countrywide Hydrogen Pty Ltd	Green Hydrogen, Mobility	Brighton
72	Hydrogen Launceston Project	Countrywide Hydrogen Pty Ltd, Launceston Airport	Green Hydrogen	Western Junction
73	Hydrogen Microgrid and Mobility Project	Blue Economy CRC, Metro Tasmania	Green Hydrogen, Mobility	Hobart
74	Origin Tasmanian Green Hydrogen and Ammonia Plant	Origin Energy, Mitsui O.S.K. Lines	Green Hydrogen, Ammonia	Bell Bay
75	Whaleback Energy Park	Westcoast Renewable Energy	Green Hydrogen	West Coast
#	**ACT**			
76	Hydrogen Test Facility - ACT Gas Network	Evoenergy, Canberra Institute of Technology	Hydrogen Gas	CIT Fischyk Campus
77	Renewable Hydrogen Refuelling Pilot	ACT Government, Neoen, ActewAGL, Hyundai, sgfleet	Refuelling Infrastructure	Canberra

Source: CSIRO - HyResource

WESTERN AUSTRALIA & NORTHERN TERRITORY

#	Project name	Key Parties	Type of project	Location
	WA			
78	Arrowsmith Hydrogen Project	Infinite Blue Energy, Xodus Group	Green Hydrogen, Hydrogen Mobility	Dongara
79	ATCO Hydrogen Blending Project	ATCO Gas Australia Pty Ltd	Hydrogen Gas	Jandakot
80	Australian Renewable Energy Hub	BP (Operator), Intercontinental Energy, CWP Global, and Macquarie Capital and Macquarie's Green Investment Group	Green Hydrogen, Export	Pilbara
81	Boolathana Project	Gascoyne Green Energy	Hydrogen, Ammonia	Gascoyne region
82	Bristol Springs Solar Hydrogen Project	Frontier Energy Ltd	Green Hydrogen	Bristol Springs
83	Christmas Creek Renewable Hydrogen Mobility Project	Fortescue, Hyzon	Hydrogen Mobility	Christmas Creek
84	Clean Energy Innovation Hub	ATCO Australia Pty Ltd	Green Hydrogen, Microgrid	Jandakot
85	Collie Battery and Hydrogen Industrial Hub Project	Sunshot Industries	Hydrogen	Collie
86	Denham Hydrogen Demonstration Plant (WA)	Horizon Power	Hydrogen, Microgrid	Denham
87	Early Production System: MEG-HP1	Infinite Green Energy Ltd, Samsung C&T, Doral Group	Hydrogen Mobility	Northam
88	East Kimberley Clean Energy Project	Aboriginal Clean Energy Partnership (Balanggarra Ventures Limited, MG Corporation, Kimberley Land Council, Pollination)	Green Hydrogen, Ammonia	East Kimberley
89	Geraldton Export-Scale Renewables Investment	BP	Green Hydrogen, Ammonia	Geraldton
90	Kwinana Clean Fuels Hub	BP, Macquarie Capital	Green Hydrogen	Kwinana
91	H2Perth	Woodside Energy Ltd	Green Hydrogen, Ammonia	Perth
92	The Hazer Process; Commercial Demonstration Plant	Hazer Group Ltd	Hydrogen, Graphite	Woodman Point
93	Hydrogen Refueller Station Project	ATCO Gas Australia Pty Ltd, Fortescue Metals Group	Hydrogen Mobility	Jandakot
94	HyEnergy (Zero Carbon Hydrogen)	Province Resources, Ozexco Pty Ltd, Total Eren	Green Hydrogen	Glascoyne Region, Carnarvon
95	Joint Feasibility Study for Creation of a Supply Chain of Low Carbon Ammonia in WA	Mitsui & Co. Ltd, Japan Oil, Gas and Metals National Corporation (JOGMEC)	CCS Ammonia	Perth
96	Mid West Clean Energy Project	Pilot Energy	Green Hydrogen, CCS	Mid West WA

	Project name	Key Parties	Type of project	Location
97	Murchison Renewable Hydrogen Project	Hydrogen Renewables Australia, Copenhagen Infrastructure Partners	Green Hydrogen	Murchison
98	Parmelia Green Hydrogen Project	APA Group, Wesfarmers	Hydrogen Transport	Kwinana
99	Project Haber	Strike Energy	Hydrogen, Ammonia	Mid West
100	Western Green Energy Hub	InterContinental Energy, CWP Global, Mining Green Energy Ltd	Green Hydrogen	Dundas, Kalgoorlie-Boulder
101	YURI Project/Yara Pilbara Renewable Ammonia	ENGIE, Yara	Green Hydrogen, Ammonia	Burrup
#	NT			
102	Darwin Clean Hydrogen Hub – Market Development Study	INPEX, Santos	Green Hydrogen	Darwin
103	Darwin Green Liquid Hydrogen Export Project and Hydrogen Hub Development	Lattice Technology (Korea) Co. Ltd	Hydrogen Export	Darwin
104	Darwin H2 Hub	Total Eren Australia H2 Pty Ltd	Green Hydrogen	Darwin
105	Desert Bloom Hydrogen	Axcentium Pty Ltd trading as Aqua Aerem	Green Hydrogen	Tennant Creek
106	Green Springs Project	Climate Impact Capital Limited (CIC)	Green Hydrogen	Western Davenport
107	Tiwi H2	Provaris Energy Ltd	Hydrogen Export	Tiwi Islands

Source: CSIRO - HyResource

HYDROGEN CHEAT SHEET

HYDROGEN CHEAT SHEET

Hydrogen's future significance in energy lies in its versatile role as a clean energy carrier, helping enable decarbonisation across challenging sectors.

It will help provide versatile energy storage and will benefit from ongoing technological advancements to foster a sustainable and resilient energy landscape.

Hydrogen will play an important role in energy, fuel cells, transportation, industrial processes, and chemical production.

KEY VECTORS

HYDROGEN (H_2)

- Hydrogen is the lightest and simplest chemical element.
- It is commonly formed through natural gas reforming or water electrolysis.
- There are diverse applications including: use as a fuel in fuel cells for vehicles, as a reducing agent in industrial processes, and as a component in ammonia and other related vectors.

AMMONIA (NH_3)

- Ammonia is a compound made up of one nitrogen atom bonded to three hydrogen atoms. It is a colourless gas with a pungent smell.
- It is often formed through the Haber-Bosch process, where nitrogen gas (N_2) from the air reacts with hydrogen gas (H_2) under high pressure and temperature.
- It is widely used in agriculture as a fertilizer. It is also used in refrigeration systems, as a cleaning agent, and in the manufacturing of various chemicals.

SYNTHETIC METHANE (CH_4)

- Synthetic methane, also known as synthetic natural gas (SNG), is a human-made or synthetic version of methane gas, the primary component of natural gas.
- It is formed through a process called methanation, where carbon dioxide (CO_2) and hydrogen (H_2) react to produce methane. The hydrogen needed for this process can be obtained through electrolysis.
- It can be used as a sustainable energy source, injected into existing natural gas pipelines, used for heating, electricity generation, or as fuel for vehicles.

METHANOL (CH_3OH)

- Methanol is an alcohol that is commonly used as an industrial solvent and fuel.
- Methanol is typically produced through a chemical process called synthesis gas production, where carbon monoxide (CO) and hydrogen (H_2) react. This synthesis gas is then further processed to form methanol.
- Methanol has applications across: being used as a fuel, antifreeze, solvent, and in the production of chemicals and plastics. Additionally, it is used in other chemical derivatives and is being explored as a potential renewable fuel source.

KEY USES

- Fuel cells: Hydrogen is a primary fuel for fuel cells, with applications in vehicles, backup power systems, and stationary power generation.
- Transportation: Hydrogen is used as a clean fuel for various modes of transportation, including hydrogen-powered vehicles such as cars, buses, trucks, and trains, offering low or zero emission mobility.
- Industrial processes: In industries such as refining, metal production, and chemical manufacturing, hydrogen serves as a crucial reducing agent, enabling processes like desulfurisation and ammonia production.
- Energy storage: Hydrogen acts as a storage medium for excess renewable energy. Excess renewable energy not used by the grid can be used to power electrolysis to produce hydrogen, which can be stored and used later when demand is high.
- Chemical production: Hydrogen is a key element in the production of various chemicals including ammonia for fertilizers, methanol, and in petroleum refining processes.

CONVERSION FACTORS

BASIC CONVERSION FACTORS

Weight Conversions

	Metric tonne	Kilogram	Short ton
Metric tonne	1	1000	1.1023
Kilogram	0.001	1	0.0011023
Short ton	0.907185	907.185	1

Temperature Conversion

	˚C	˚F
˚C	0	32
˚F	-17.7778	0

Pressure Conversion

	Bar	Pascal (P)	megaPascal (MPa)
Bar	1	100000	0.1
Pascal	0.00001	1	0.000001
megaPascal (MPa)	10	1000000	1

Volume/Energy Conversions

	Kilowatt hour (kWh)	Joule (J)	Megajoule (MJ)
Kilowatt hour (kWh)	1	3,600,000	3.6
Joule (J)	2.77778×10^{-7}	1	1×10^{-6}
Megajoules (MJ)	0.277778	1000000	1

	Weight		Gas		Liquid	
	pounds (lb)	kilograms (kg)	cubic feet (scf)	cu meters (Nm^3)	gallons (gal)	litres (l)
1 pound	1.0	0.4536	191.26	5.4159	1.6925	6.407
1 kilogram	2.2046	1.0	1 421.66	11.940	3.37313	14.125
1 scf gas	0.005309	0.002408	1.0	0.02679	0.008985	0.03401
1 Nm^3 gas	0.1982	0.08989	37.327	1.0	0.3354	1.2697
1 gallon liquid	0.5908	0.2680	113.0	2.9815	1.0	3.7855
1 litre liquid	0.1561	0.07080	29.852	0.8453	0.2642	1.0

Scf (standard cubic foot) gas measured at 1 atmosphere and 60°F.
Nm^3 (normal cubic meter) gas measured at 1 atmosphere and 0°C.
Liquid measured at 1 atmosphere and boiling temperature.

	Kilowatt (kW)	Megawatt (MW)
1 Kilowatt (kW)	1	0.001
1 Megawatt (MW)	1000	1

THERMODYNAMIC PROPERTIES OF HYDROGEN[265]

Parameter	Value
Hydrogen HHV (ΔH)	-286 kJ/mol
Hydrogen LHV (ΔH)	-242 kJ/mol
Energy content of 1 kg hydrogen	141.9 MJ (HHV) = 0.1419 GJ = 39.4 kWh
	120.1MJ (LHV) = 0.1201 GJ = 33.3 kWh
Energy content of 1 N-m^3 hydrogen	12.7 MJ (HHV) = 0.0127 GJ
Energy content of 1 gallon of gasoline	121.3 MJ (LHV) = 0.1213 GJ

ΔH = Enthalpy (total heat content of the system, negative enthalpy indicates ectothermic reaction)

kJ = Kilojoule (=1000 joules)

HHV = Higher Heating Level (the upper limit of available thermal energy produced by the complete combustion of hydrogen)

LHV = Lower Heating Level (amount of heat released by combusting a specified quantity and returning the temperature of the combustion products to 150˚C)

GLOSSARY

- AEM: Anion Exchange Membrane; An electrolyser technology that uses low cost transition metal catalysts with a semipermeable membrane to allow anions to pass (as opposed to using precious metals).
- Alkaline Technology: An electrolyser technology that splits water into its constituents through voltage being applied to two electrodes in a caustic electrolyte solution - frequently potassium hydroxide.
- Ammonia: An inorganic chemical composed of nitrogen and hydrogen, with its chemical form being NH_3. Ammonia is a carrier of hydrogen, and is used in applications such as fertilisers, chemical feedstock and explosives.
- ARENA: Australian Renewable Energy Agency; Established by the Australian Govovernment to provide funding and improve the competitiveness of renewable energy technologies and increase the supply of renewable energy through innovation that benefits Australian consumers and businesses.
- ATR: Autothermal Reforming; A process for producing syngas, composed of hydrogen and carbon monoxide, by partially oxidizing a hydrocarbon feed with oxygen and steam, and subsequent catalytic reforming.
- Bar: A metric unit of pressure.
- BEV: Battery Electric Vehicles; A type of EV that exclusively uses chemical energy stored in rechargeable battery packs, with no secondary source of propulsion. BEVs use electric motors and motor controllers instead of internal combustion engines.
- Blue Hydrogen: Hydrogen produced through fossil fuels and SMR or gasification, but with carbon emissions captured.
- BOF: Basic Oxygen Furnace; A steelmaking method in which pure oxygen is blown into a bath of molten blast-furnace iron and scrap.
- BoP: Balance of Plant costs; All the supporting components and auxiliary systems needed to deliver the energy, other than the generating unit itself. These may include transformers, inverters, supporting structures etc.
- Brown Hydrogen: Produced from coal through gasification. Material carbon emissions released during production.
- Capacity Utilisation: The manufacturing/production capabilities that are being utilised by a hydrogen at any given time. It is the relationship between the output produced with the given resources and the potential output that can be produced if capacity was fully used.
- Cap-And-Trade: A system for controlling carbon emissions by which an upper limit is set on the amount an organisation may produce, but which allows further capacity to be bought from other organisations that have not used their full allowance.
- CCS/CCUS: Carbon, Capture and Storage/Carbon, Capture, Utilisation and Storage; An integrated suite of technologies that captures CO_2 from being released into the atmosphere. CCUS does not include the permanent geological storage of CO_2.
- CEFC: Clean Energy Finance Corporation.
- Cell Stack: The fuel cell stack is the heart of a fuel cell power system. It generates electricity in the form of direct current (DC) from electro-chemical reactions that take place in the fuel cell.
- CO_2 Cluster: Refers to a grouping of individual CO_2 sources, or to storage sites such as multiple fields within a region. The Permian Basin in the US has several clusters of oilfields undergoing CO_2 -EOR fed by a network of pipelines.
- CO_2 Hub: A hub collects CO_2 from various emitters and redistributes it to single or multiple storage locations.
- CO_2 Network: An expandable collection and transportation infrastructure providing access for multiple emitters.
- Compressed Hydrogen: The gaseous state of the element hydrogen kept under pressure. Compressed hydrogen can range from 350-1000 bar and is used in mobility, storage, transport and refuelling applications.
- Cracking: A type of sour corrosion that occurs especially in carbon and low alloy steel when atomic hydrogen diffuses into the inclusions and trap sites of steel and combines to form molecular hydrogen in void spaces.
- Cryogenic Tank: A tank that is used to store material (such as liquid hydrogen) at very low temperatures.
- Curtailment: The act of reducing or restricting energy delivery from a generator to the electrical grid.
- De-ionised Water: Often synonymous with demineralised water, is water that has had almost all of its mineral ions removed, such as cations like sodium, calcium, iron and copper, and anions such as chloride and sulfate. Deionisation produces highly pure water that is generally similar to distilled water, with the advantage that the process is quicker and does not build up on scale.
- Density: The degree of compactness of a substance.
- Distributed Power (Hydrogen): Hydrogen for use in stationary power generation microgrids for the power utility industry and industrial sites.
- DRI: Direct Reduced Iron; This involves splitting natural gas into a mix of carbon monoxide and hydrogen, and using these gases to reduce iron ore to iron metal.
- EAF: Electric Arc Furnace Steelmaking; Electric Arc Furnace is a steelmaking furnace, in which steel scrap is heated and melted by heat of electric arcs striking between the furnace electrodes and the metal bath. The main advantage EAF over BOF is their capability to treat charges containing up to 100% of scrap. About 33% of the crude steel in the world is made in EAF.
- EIA: Environmental Impact Assessment; Environmental Impact Assessment is a process of evaluating the likely environmental impacts of a proposed project or development, taking into account inter-related socio-economic, cultural and human-health impacts, both beneficial and adverse.
- Electrode: A conductor through which electricity enters or leaves an object, substance, or region.
- Electrolyte Solution: A solution that generally contains ions, atoms or molecules that have lost or gained

electrons, and is electrically conductive (often called ionic solutions).

- Embrittlement: A partial or complete loss of a material's (commonly steel) ductility, thus making it brittle.
- Energy Transition: Energy transition refers to the global energy sector's shift from fossil-based systems of energy production and consumption— including oil, natural gas and coal — to renewable energy sources like wind and solar, as well as lithium-ion batteries.
- EU ETS: European Union Emissions Trading Scheme; The EU ETS is a cornerstone of the EU's policy to combat climate change and its key tool for reducing greenhouse gas emissions cost-effectively. It is the world's first major carbon market and remains the biggest through a cap and trade principle.
- FAT: Factory Acceptance Test; Helps verify that newly manufactured and packaged equipment meets its intended purpose. The FAT validates the operation of the equipment and makes sure the customers' purchase order specifications and all other requirements have been met.
- FCEV: Fuel Cell Electric Vehicles; An electric vehicle that uses a fuel cell, sometimes in combination with a small battery or supercapacitor, to power its onboard electric motor. Fuel cells in vehicles generate electricity generally using oxygen from the air and compressed hydrogen.
- Feasibility Study: An assessment of the practicality of a proposed plan or method.
- Fossil Parity: Happens when the use of renewable energies cost less than, or equal to, the price of using power from conventional sources such as coal, oil and natural gas (fossil fuels). Also known as grid parity.
- Gas Blending (Hydrogen): Hydrogen blending into natural gas pipelines/networks for large scale gas supply or energy storage.
- Gasification: The process of producing syngas under controlled conditions through partial oxidation of coal.
- GHG: Greenhouse Gas.
- Green Hydrogen: Produced through electrolysis of water using a renewable power source. Zero carbon emissions in production.
- Grey Hydrogen: Produced from methane or natural gas through steam methane reforming. Material carbon emissions released during production.
- Grid Stabilisation (Hydrogen): Hydrogen for use in stationary power generation for grid stabilisation – optimising power from base load for the power utility industry.
- Guarantee of Origin: Allows for a standardised process of tracing and certifying the provenance of hydrogen and the associated environmental impacts.
- H_2: Hydrogen in molecular form.
- HDPE: High Density Polyethylene; A hydrocarbon polymer prepared from ethylene/petroleum by a catalytic process; A kind of thermoplastic which is famous for its tensile strength and ability to withstand high temperatures.
- Hydride: A binary compound of hydrogen with a metal.
- Hydrocarbons: Hydrogen chemically bonded with carbon.
- ICE: Internal Combustion Engine.
- IEA: International Energy Agency; An autonomous intergovernmental organisation established to shape a secure and sustainable future for all.
- Industrial Feedstock (hydrogen): Hydrogen feed for various industrial processes to produce an end product, such as ammonium nitrate.
- Industrial Separation: The separation of CO_2 from other gases produced at large industrial process facilities such as coal and natural-gas-fired power plants, steel mills, cement plants and refineries.
- Ion-exchange Membrane: An ion-exchange membrane is a semi-permeable membrane that transports certain dissolved ions, while blocking other ions or neutral molecules. Ion-exchange membranes are therefore electrically conductive.
- IPCC: Intergovernmental Panel on Climate Change; The United Nations body for assessing the science related to climate change.
- IRA: Inflation Reduction Act (United States policy).
- kW: Kilowatts.
- LCOE: Levelised Cost of Electricity; A measure of the average net present cost of electricity generation for a generating plant over its lifetime. It is used for investment planning and to compare different methods of electricity generation on a consistent basis.
- Liquefaction: The process of making something, especially a gas, liquid.
- LNG: Liquefied Natural Gas.
- LOHC: Liquid Organic Hydrogen Carrier.
- LPG: Liquefied Petroleum Gas.
- Material Handling: Equipment used for the movement, protection, storage and control or products throughout manufacturing, warehousing, distribution and consumption processes.
- Methylcyclohexane (MCH): An organic compound classified as saturated hydrocarbon. It is a colourless liquid with a faint odour and can be used as a solvent. It is mainly converted in naphtha reformers to toluene.
- MGO: Marine Gasoil.
- MJ/kg: Mega joules per kilogram; A measurement of specific kinetic energy.
- MMV: Monitoring, Measurement and Verification; Plays a vital role in ensuring CO_2 storage site occurs over its entire lifecycle from pre-injection to operations to post-injection.
- Mobility (Hydrogen): Hydrogen for use in powering transport and other mobility applications including maritime, light and heavy vehicle.
- $MtCO_2$: Metric tons of carbon dioxide equivalent. A metric measure used to compare the emissions from different greenhouse gases based upon their global warming potential (GWP).
- MWh: Megawatt hour.

- Net Zero Carbon Emissions: Refers to achieving an overall balance between greenhouse gas emissions produced and greenhouse gas emissions taken out of the atmosphere.
- NH3: Ammonia in molecular form.
- Nm3/h: Normal meter cubed per hour; Unit used to measure gas flow rate.
- Oxy-Combustion: Oxy-fuel combustion is the process of burning a fuel using pure oxygen, or a mixture of oxygen and fuel gas, instead of air. Since the nitrogen component of air is not heated, fuel consumption is reduced, and higher flame temperatures are possible.
- PEM Technology: Polymer Electrolyte Membrane; An electrolyser technology that creates a reaction using an ionically conductive solid polymer, rather than a liquid.
- Petrochemicals: The chemical products obtained from petroleum by refining. Some chemical compounds made from petroleum are also obtained from other fossil fuels, such as coal or natural gas, or renewable sources such as maize, palm fruit or sugar cane.
- Pink Hydrogen: Hydrogen through electrolysis when the electrical energy comes from nuclear power, as opposed to renewables.
- Pipelines: Long pipes, typically underground, for conveying oil, gas, hydrogen, etc. over long distances.
- Post-Combustion: The removal of CO_2 from power station flue gas prior to its compression, transportation and storage in suitable geological formations, as part of carbon capture and storage.
- POX: Partial Oxidation; Partial oxidation is a type of chemical reaction. It occurs when a substoichiometric fuel-air mixture is partially combusted in a reformer, creating a hydrogen-rich syngas which can then be put to further use, for example in a fuel cell.
- PPA: A power purchase agreement, or electricity power agreement, is a contract between two parties, one which generates electricity and one which is looking to purchase electricity.
- Pre-Combustion: Pre-combustion capture refers to removing CO_2 from fossil fuels before combustion is completed. For example, in gasification processes a feedstock (such as coal) is partially oxidized in steam and oxygen/air under high temperature and pressure to form synthesis gas.
- Purple Hydrogen: Also known as Pink Hydrogen.
- Red Hydrogen: Also known as Pink Hydrogen.
- Refuelling Station: Fuelling stations are repositories of fuel (including hydrogen) that have been located to service commercial and naval vessels.
- Salt Cavern: Artificial cavities in underground salt formations, which are created by the controlled dissolution of rock salt by injection of water during the solution mining process.
- Sequestration: Carbon sequestration is the process of capturing and storing atmospheric carbon dioxide. It is one method of reducing the amount of carbon dioxide in the atmosphere with the goal of reducing global climate change through either geologic or biologic methods.
- Skid-Mounted Module: A skid mount is a popular method of distributing and storing machinery and usually-stationery equipment. Simply put, the machinery at point of manufacture is permanently mounted in a frame or on to rails or a metal pallet.
- SMR: Steam Methane Reforming; A method for producing syngas by reaction of hydrocarbons with water. Commonly natural gas is the feedstock. The main purpose of this technology is hydrogen production.
- Syngas: A fuel gas mixture consisting primarily of hydrogen, carbon monoxide, and very often some carbon dioxide. The name comes from its use as an intermediate in creating synthetic natural gas and for producing ammonia or methanol.
- Synthetic Hydrocarbons: Synthetic liquid fuels (e.g. gasoline, diesel, jet-fuel equivalent).
- tCO_2: Total carbon dioxide; Measure of carbon dioxide which exists in several states.
- Turquoise Hydrogen: Produced when natural gas is broken down with the help of methane pyrolysis into hydrogen and solid carbon. The process is driven by heat produced with electricity, rather than through the combustion of fossil fuels. Where the electricity driving the pyrolysis is renewable, the process is zero-carbon.
- UAV: Unmanned Aerial Vehicles.
- Vector: An alternative substance, form or method of energy transportation such as transporting a gas in liquid form.
- White Hydrogen: A naturally-occurring geological hydrogen found in underground deposits and created through fracking.
- Yellow Hydrogen: Hydrogen through electrolysis when the electrical energy comes from grid electricity, as opposed to renewable.

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WITH SPECIAL THANKS TO...

Alexandra Cooper, Andrew Leeds, Bonny Cheng, Chris Kermeen, Grant Bransgrove, Nick Easingwood, Sachiko Robinson, Shane White, Siobhan Jordan, Stephen Toohey

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IMPORTANT NOTICE

Australia and New Zealand Banking Group Limited (ANZ) ABN 11 005 357 522, a company incorporated in Australia AU23722. Item No. 97850 03.2024 WZ138590