**#1** Stay on top with the #1 Institutional bank across Australia, New Zealand & Asia

THE ANZ

# HYDROGEN HANDBOOK - AH2

2022

# No.1 Relationship Strength Index in the Peter Lee Associates Large Corporate & Institutional Relationship Banking surveys, Australia 2014-21 and New Zealand 2010-21. No.1 Overall Relationship Quality in the Greenwich Associates Asian Large Corporate Banking studies, 2017-21.

# CONTENTS

# FOREWORD

The global push to reduce carbon emissions to net-zero by 2050 is intensifying, with every sector of the economy increasing targets and focus. Even so, much of this continues to be shouldered by the rapid changes happening right across the entire supply chain in the energy sector – in power generation, transmission and retail.

The financial services sector will play a key role, with investors and intermediaries such as banks and insurers providing capital and risk mitigation for the trillions of dollars needed to fund the global recalibration towards net-zero.

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.

ANZ's Climate Change Commitment focuses on supporting customers through this transition and reducing our own impact as an organisation. This includes engaging with 100 of our largest emitting customers to support their transition plans and sustainability ambitions.

We are also disclosing more robust and credible metrics to enable the emissions impact of our financing to be tracked annually, starting with pathways and targets for commercial property and power generation in 2021.

The rapid emergence of hydrogen as a low-emissions fuel source offers another pathway to achieving net-zero carbon. With its distinctive properties as an energy carrier, we believe hydrogen will be key to de-carbonisation across broad sectors of the economy, particularly transportation, heavy industry and manufacturing.

With abundant wind and solar energy resources, Australia is well positioned to play a pivotal role in developing a hydrogen export market to key customers in Asia, in particular those in Japan, Singapore and South Korea. Our customers are clearly pursuing the commercial production of hydrogen to varying degrees.

However, the commercialisation of hydrogen does have challenges, particularly around the costs associated with safe storage and transportation. Electrolysis, the main method of producing renewable hydrogen at scale, comes at considerable expense.

While hydrogen's unique properties as an energy carrier is much touted, the gas is highly flammable and volatile. It also has a lower density than gasoline and must be stored in cooler temperatures to maintain its liquid form and effectiveness as a fuel source. The liquefaction and transportation of hydrogen under high pressure also requires significant and expensive storage infrastructure.

As part of ANZ's ambition and commitment to be the leading Australia- and New Zealand-based bank in supporting customers' transition to net zero emissions, our goal is to be the go-to bank for the emerging sustainable hydrogen economy, helping customers develop new technologies, products and services. Notwithstanding the challenges of developing large-scale hydrogen for industrial usage, there is significant momentum alongside strong Australian Federal and State Government support in the start-up phase of the industry.

Given our role in financing transition, we saw a growing need for a resource like the ANZ Hydrogen Handbook to give readers up-to-date, insightful and practical information on the emerging hydrogen economy.

We hope you find the Handbook helpful in understanding - and acting on - this exciting opportunity.

**Shayne Elliott**
Chief Executive Officer
ANZ

**Mark Whelan**
Group Executive
Institutional, ANZ

**Christina Tonkin**
Managing Director
Corporate Finance, ANZ

# HYDROGEN –
# IS IT A LOT OF HOT AIR?

Research Paper

Author:
**John Hirjee**

# HYDROGEN 101

## WHAT IS IT?

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

## WHY HYDROGEN?

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 burned.
- It is an excellent carrier of energy, with each kilogram of hydrogen containing about 2.4 times as much energy as natural gas[1]. This energy can be released as heat through combustion, or as electricity using a fuel cell. In both cases the only other input needed is oxygen, and the only by-product is water.

Using hydrogen in place of fossil fuels therefore offers a pathway to decarbonise energy systems. At a global level, replacing fossil fuel use with carbon-free hydrogen will significantly reduce greenhouse gas emissions.

The 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 water, biomass, minerals and fossil fuels.

## HOW IS IT PRODUCED?

The most common production methods include **electrolysis** (the use of electricity from renewable energy sources to split water molecules into hydrogen and oxygen), or through **thermochemical reactions** (utilising steam-methane reforming, gasification or pyrolysis processes with fossil fuels). With the application of carbon capture, utilisation and storage (CCS/CCUS) to the latter, 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.

### Blue Hydrogen

In fossil fuel-based thermochemical processes used to produce hydrogen, energy from the fossil fuel drives chemical reactions that lead to extraction of hydrogen. In almost all cases $CO_2$ is a by-product. Some form of CCS/CCUS is essential to deliver the decarbonisation benefits.

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.

### Green Hydrogen

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

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

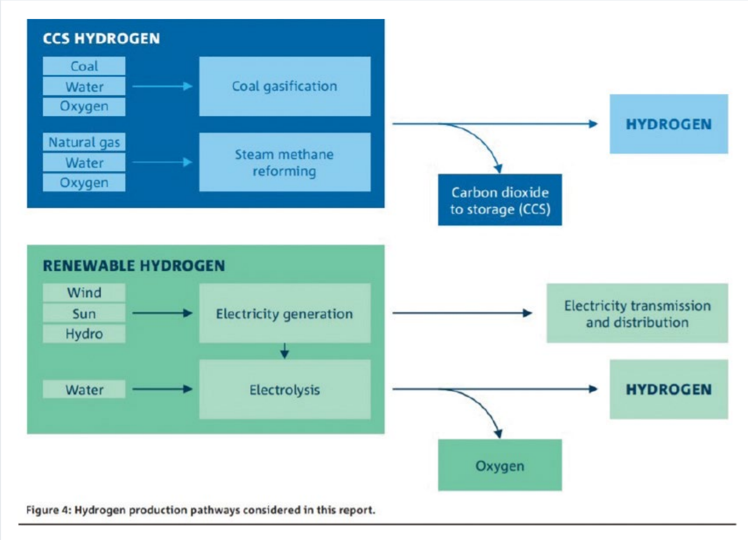
Hydrogen production via electrolysis requires high- purity water. The majority of commercial electrolysers have an integrated deioniser to purify the water. For every 1 kg of hydrogen produced, a minimum of approximately 9 kg of water is required[2]. To get a sense of the amount of water required for large-scale hydrogen production, consider the challenge of producing enough hydrogen to match the energy content of Australia's LNG production. Australia's LNG exports in the 2022 fiscal year are projected to be around 83 million tonnes[3]. 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 very small proportion of Australia's current annual water consumption, and about half of the water used in Australian mining.

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[4].

**Hydrogen production from biomass**

The reforming and gasification processes described above can also be used to produce hydrogen or biofuels from residual biomass from forestry, agriculture or from waste from human activities.

Hydrogen produced in this way can be considered low emissions since the $CO_2$ released from the biomass came from the atmosphere in the first place. However, some emissions may be created from collecting the biomass. Technologies such as the Hazer Process which produces solid graphite instead of $CO_2$ are undergoing pilot project and testing activities. Hydrogen production using biomass can result in net negative emissions if CCS is used. But these biomass production processes would be challenging to do at scale, due to feedstock availability and variability as well as transport costs.




Green and blue hydrogen (chiefscientist.gov.au)

## THE ECONOMICS OF HYDROGEN PRODUCTION

Currently, fossil fuel-based processes produce hydrogen at a lower cost than renewable electricity electrolysis technologies. In 2020, hydrogen from natural gas without CCS cost in the range of $A3-4/kg hydrogen[5], depending on local gas prices. These costs are expected to drop over time, with costs forecast to lower to a range of $A1.70-2.20/kg hydrogen in 2050. 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 cost of capital expenditure, coal availability and cost. For Australia, if brown coal is the gasification fuel, the coal input cost would be significantly reduced due to its easy accessibility, abundance and very low price.

The table below compares current energy efficiencies, costs, and $CO_2$ emissions of the most widely used production processes. It shows that the fossil fuel-based processes produce the cheapest hydrogen, and that low emissions can be achieved if CCS is available. While renewable electricity electrolysis technologies currently produce hydrogen at a higher cost, they do so with inherently low emissions. While electrolysis technology is still relatively immature, ongoing volume driven innovation is expected to bring process costs down further in the near to mid- term, becoming competitive with thermochemical production processes by 2025 according to the CSIRO[6]. The US Department of Energy has a cost target for hydrogen by electrolysis of US$2.30/kg (about A$3.10/kg), in line with the estimates by the CSIRO for 2025[7].

CCS costs are highly location dependent and the technology has not yet achieved full widespread commercialisation. The process emissions figures in the below table assume 95% capture efficiency for gasification with CCS, and 90% for SMR with CCS. Note, these process emission figures are not the same as the emissions saved by retiring fossil fuel use in the importing country.

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[8].

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 $2/kg with the landed costs of natural gas in importing countries[9].

## WHAT IS THE MARKET FOR HYDROGEN?

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

Global demand for hydrogen in 2020 was about 88.5 million tonnes (Mt) a year (with the same energy content as 212 Mt of LNG)[11]. By comparison, Australia exported 60 Mt in FY18. Historically, the majority of hydrogen production has been used to refine oil or produce ammonia and other chemicals for the production of fertilisers and plastics.

| Production Process | Primary Energy Source | Hydrogen Production Energy Efficiency (%, Lhv) | Hydrogen Production Cost A$/kg | | Hydrogen Production Cost A$/Gj (Lhv) | | Emissions In kg $Co_2$/Gj Of Hydrogen |
|---|---|---|---|---|---|---|---|
| | | | 2018 Estimate | 2025 Best Case Model | 2018 Estimate | 2025 Best Case Model | |
| Steam methane reforming *with* CCS | Natural gas | 64 | 2.30-2.80 | 1.90-2.30 | 19.20-23.30 | 15.80-19.20 | 0.76 |
| Coal gasification *with* CCS | Coal | 55 | 2.60-3.10 | 2.00-2.50 | 21.70-25.80 | 16.70-20.80 | 0.71 |
| Alkaline electrolysis | Renewable electricity | 58 | 4.80-5.80 | 2.50-3.10 | 40.00-48.30 | 20.80-25.80 | ~0 |
| PEM electrolysis | Renewable electricity | 62 | 6.10-7.40 | 2.30-2.80 | 50.80-61.70 | 19.20-23.30 | ~0 |

Costs, efficiencies and $CO_2$ emissions from different hydrogen production pathways (hydrogencouncil.com)

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 despatchable electricity generation.

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, whilst 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 over 3 million tonnes per year by 2040, which could be worth up to US$10 billion per year to the economy[12].

Key end uses for hydrogen in these markets are:

- Powering fuel cell vehicles including heavy haulage trucking fleets.
- Industrial heat (e.g. kilns, calciners).
- Large-scale and residential electricity generation.
- Blending into natural gas networks.
- Industrial feedstock.
- Grid stabilisation.
- Shipping vessels and prime movers.

Road transport is responsible for about 15% of carbon emissions, with rail, sea and air transport accounting for 3%[13]. Ultralow emissions vehicles – battery electric vehicles (BEV) and fuel cell electric vehicles (FCEV) – are therefore key to reducing emissions.

Both BEVs and FCEVs use an electric drivetrain. In BEVs, electricity from an external supply charges a battery, which in turn supplies electricity for the motor. In FCEVs, electricity for the motor is generated by a fuel cell using hydrogen. Both vehicle types produce zero tailpipe emissions, making them ideal for combatting air quality issues in urban environments.

## TRANSPORTING AND STORING HYDROGEN

Hydrogen is a very light gas and requires conversion for storage and transport due to it's 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 ($NH_3$)

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 current view is that up to c.15% hydrogen can be used in existing pipeline networks[14]. The Hyp SA project begun earlier this year in South Australia introducing up to 5% hydrogen in existing pipelines to monitor the impact on infrastructure and household appliances[15]. Risk factors include the condition of the pipe and welds, grade of steel, thickness, types of welds and operating pressure.

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.

## AUSTRALIA'S NATIONAL HYDROGEN STRATEGY

The Federal Government and the 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.

It aims to position Australia's hydrogen industry as a major global player by 2030. It is also worth highlighting that individual states also have hydrogen strategies or programs in place.

## THE CHALLENGES FOR COMMERCIAL HYDROGEN

As pointed out by Matthew Warren, former CEO of the Australian Energy Council, in an op-ed in the AFR, global interest in developing a hydrogen economy is the product more of necessity than invention. Industries like steel and cement and heavy transport have limited options in a decarbonised world. They require a clean industrial fuel.

Energy importing industrial economies (such as Germany and Japan) increasingly see hydrogen as their best bet. The aim of green hydrogen is for the economy to be able to switch to the importation of zero emissions hydrogen as a replacement to fossil fuels.

Hydrogen has yet to break through due to its comparatively high costs and efficiency losses. Electrolysis is capital expensive and technological advancements to reduce this cost will be necessary to see the scale up of use and supply.

Once produced, hydrogen is difficult to store and move. Its small molecules mean it leaks easily. To make pipelines or shipping cost-effective, this requires methods such as compression, liquefaction or chemical compounding into substances such as ammonia or LOHCs. Each of these options presents its own challenges, for example with liquefaction requiring temperatures of -253C. By way of comparison, natural gas liquefies at around -161C. The energy needed to convert and move hydrogen efficiently can undermine its ability to compete.

## OPPORTUNITY FOR AUSTRALIA

There are three opportunities driving the push to clean hydrogen:

1. **Energy export** - Nations like Japan and South Korea that import most of their energy in the form of coal, oil and natural gas need cleaner energy to meet their $CO_2$ emissions reduction targets. Clean hydrogen is ideal. This is a significant opportunity for Australia, given the potential for ample renewable energy and convertible fossil fuel reserves. However, the export industry is likely to take some years to develop to full-scale commercialisation.
2. **Domestic economy** - Hydrogen can power our vehicles, be used in commercial heating applications, and supply our industrial processes. These represent opportunities to expand manufacturing and generate innovation and jobs while lowering $CO_2$ emissions.
3. **Energy system resilience** - While firmed renewable energy is the least capital intensive form of producing clean hydrogen, green $H_2$ production can respond rapidly to variations in electricity production and contribute to frequency control in the electricity grid.

# COLOURS OF HYDROGEN

Research Paper

Author:
**John Hirjee and Jessica Paterson**

# OVERVIEW

Hydrogen is the lightest and most abundant chemical substance in the universe. It can be produced as either a gas or liquid and can be used in a variety of applications. This odourless and invisible gas has a colourful future, and while all hydrogen burns the same, 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**<br>• Zero carbon emissions in production and combustion |
| | **Blue** | • Same production process as brown or grey hydrogen<br>• **Carbon emissions are captured** |
| | **Grey** | • Produced from **methane or natural gas** through **steam methane reforming**<br>• Material carbon emissions released during production |
| | **Brown** | • Produced from **coal** through **gasification**<br>• Material carbon emissions released during production |

| 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) into hydrogen and solid carbon. The difference is that the process is driven by heat produced with electricity, rather than through the combustion of fossil fuels.<br>• The output of carbon in solid form (rather than $CO_2$) means there is **no requirement for CCS** and the carbon can even be used in other applications, such as a soil improver or the manufacturing of certain goods such as tyres. **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 **grid electricity**. |
| | **White** | • A **naturally-occurring** geological hydrogen found in underground deposits and created through **fracking**.<br>• There are no strategies to exploit this hydrogen at present. |

# BROWN AND GREY HYDROGEN

Most hydrogen currently comes from natural gas, but this process also creates a lot of carbon waste.

The majority of chemicals in natural gas contain large amounts of hydrocarbons – hydrogen chemically bonded with carbon. Catalysts can break these bonds, but the excess carbon then creates $CO_2$[16].

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".

"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."

In conjunction with the decreasing cost of renewable electricity generation, the cost gap between grey and green hydrogen will continue to close slowly.

***Coal + Water + Heat → Gasification → Syngas***

Small town gasworks made hydrogen from coal for hundreds of years, but now industrial manufacturers colour it as "brown hydrogen". Using water and heat, coal can undergo "gasification". In this process, the chemicals within coal react to make what was known as "town gas". Now known as syngas, this contains a mixture of carbon dioxide ($CO_2$), carbon monoxide (CO), hydrogen, methane and ethylene, along with small quantities of other gases[16].

The first two of these gases have no use in power generation. This makes the process very polluting, compared to other methods. However, chemical companies can distil hydrogen from this mixture relatively simply.

As waste-to-energy incinerators become more common, they increasingly use similar processes to generate brown hydrogen. A similar process can produce syngas from biomass and petrochemicals. Despite this, the majority of syngas comes from coal[17].

Gasification projects are becoming both larger and smaller, and the regional distribution of gasification has changed significantly in recent years. Gasification plants were fairly evenly distributed between Asia and Australia, Africa and the Middle East, and North America. The gasification capacity – both operational and under construction – in the Asia/Australia region now exceeds the rest of the world put together[18].

Blue hydrogen relies on the same process as grey hydrogen, along with carbon capture and storage (CCS). This eliminates the emissions of grey hydrogen, improving the hydrogen's environmental impact.

Blue hydrogen avoids the potential future cost of carbon tariffs in exchange for the fixed cost of using CCS. Because many CCS projects form around old oil and gas fields, the existing infrastructure and compatibility of blue hydrogen make it more attractive to producers than some others[16].

The $CO_2$ produced during hydrogen production does not enter the atmosphere, due to it being deposited and stored underground, and therefore hydrogen production can be considered $CO_2$-neutral on the balance sheet.

Green hydrogen cuts out polluting chemicals entirely. It requires water and electricity, which create hydrogen using electrolysis. Electrolysis is a chemical reaction where an electric current is passed through metal conductors, known as electrodes, in water. This separates water into its component elements, hydrogen and oxygen. Using electricity originally generated by renewable sources makes this hydrogen carbon-free and consequently "green" in colour. As a result, we are seeing large investments into electrolyser technologies, with many nations implementing strong green hydrogen strategies into their decarbonisation pathways.

### What is it used for?

Australia is well placed to benefit from the growth of the hydrogen market due to its proximity to the Asia Pacific region and ability to capitalise on an already proven track record in energy exports, such as LNG.

Examples of end uses of hydrogen include:

- Green hydrogen for export
- Powering fuel cell vehicles including heavy haulage trucking fleets
- Industrial heating (e.g. kilns, calciners)
- Large-scale and residential electricity generation
- Blending into natural gas networks
- Industrial feedstock
- Grid stabilisation
- Shipping vessels and prime movers.

Green hydrogen capacity increased from 1MW in 2010 to 25MW in 2019[19]. And to further highlight the rapid rate of growth - with all the projects currently in the pipeline total installed hydrogen electrolysis capacity could reach 54-91GW by 2030[20].

# BLUE AND GREEN HYDROGEN

As a low carbon option, the debate is narrowed to blue and green hydrogen, especially in Australia as we do not have a nuclear industry (which can also be included as a low carbon option for producing hydrogen in other countries).

| Production Method | Benefits | Challenges |
|---|---|---|
| Blue | • ~90% lower $CO_2$ production than existing SMR or ATR<br>• Can produce much larger volumes of low carbon hydrogen than green at current time<br>• CCS can be retrofitted on existing SMR facilities | • CCS technology has yet to prove it can be cost effective at scale – blue $H_2$ will be contingent on a successful trajectory of this technology/process<br>• Blue hydrogen is at a premium over grey and can be exposed to price dynamics in the gas market<br>• Questions on what to do with captured $CO_2$ (storing vs alternative revenues)<br>• Still emits $CO_2$ and methane<br>• Requires availability of water |
| Green | • Facilitates zero $CO_2$ hydrogen production<br>• Production can be distributed<br>• Electrolysers can provide grid flexibility during periods of excess renewable electricity load and mitigate curtailment and/or negative power price event<br>• Once at scale, electrolyser production costs are expected to fall sharply<br>• Most of the cost of production are from electricity generation and the price of renewable power continues to fall | • Currently more expensive than any other commercialised form of hydrogen production<br>• Electrolyser manufacturing will require scaling<br>• Many electrolyser technologies still in early piloting/ testing stages<br>• Additional build out of firm renewable electricity generation capacity will be required<br>• Some electrolyser technologies require precious metals and use of those metals will need to be reduced or eliminated in order to meet major cost reductions<br>• In order for the hydrogen to be "green" the electricity source(s) will need to be 100% zero carbon. There may be issues with availability and/or guaranteeing authenticity of original power source<br>• Requires significant input of deionised water |

# FINAL THOUGHTS

With further advancements in technology, the decline in the cost of renewables and increased incentives within the market, hydrogen is positioning itself to play a major role in global **decarbonisation**.

In order 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.

Since 2018, an estimated A$1.5 billion has been awarded by Australian Governments or research institutions to progressing clean hydrogen projects and supportive activities[21]. This funding has enabled exponential development of regional hydrogen hubs and feasibility studies/research programs for Australia to take advantage of this global momentum. In addition, a large proportion of Australia's top trading partners have already committed to using clean hydrogen to decarbonise their energy systems, affording Australia the opportunity to build a lucrative export industry valued in the billions, as well as enhanced national energy security and emissions reductions.

**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, however a number of its properties make it safer to handle and use in comparison to other commonly used fuels. Hydrogen is non-toxic and due to its light density, it dissipates quickly when released allowing for relatively 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 in order 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 whilst 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, whilst capture technologies are well- developed, limited application in most industries increases perceived risk and regulatory comfortability. However, emissions reduction commitments require the adoption of a range of technologies and mitigation solutions and the acceptance of CCS projects are indeed 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. In order to achieve an **equilibrium between supply and demand** of hydrogen, this will entail further infrastructure build-out requirements and increased energy affordability moving forward;
- And finally, in regards to **implications for other industries**, hydrogen should be seen as an opportunity for oil and gas producers and infrastructure operators to expand the terminal of their assets. While the ramp up of a green hydrogen economy may take some 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.

# HYDROGEN ELECTROLYSERS

INSIDE



Research Paper
Author:
**Jessica Paterson**

# EXECUTIVE SUMMARY

## OVERVIEW

- A hydrogen electrolyser is a highly complex piece of equipment which uses an electrical current to convert water molecules ($H_2O$) into its composite parts – hydrogen ($H_2$) and oxygen ($O_2$)[22]. 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, such as solar or wind power, the hydrogen has no carbon footprint and is considered "green hydrogen".
- Alternatively, hydrogen electrolysers may also be used theoretically to produce "red hydrogen" (using nuclear power as opposed to renewables), and "yellow hydrogen" (using grid electricity).
- Electrolysers enable the user to not just generate hydrogen, but to also be used to 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.
- And furthermore, electrolysers are designed as prefabricated skid-mounted modules, which can be combined/stacked easily to scale up production capacity as required.
- In 2020, green hydrogen only constituted 0.1% 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 EUR10 trillion market globally[24].
- According to the IEA, 17GW of global hydrogen electrolyser capacity is planned to be commissioned by 2026, compared to 0.3GW in 2020[25].
- Therefore, in recent years, production of electrolysers has ramped up significantly to meet the global demand for green hydrogen, which will play a central role in the further development and completion of the energy system transition.
- For Australia to achieve its goal of becoming a global leader in low emissions technology, and for corporations to meet their targets of net zero emissions, hydrogen must be in the nation's energy mix.

# TECHNOLOGIES

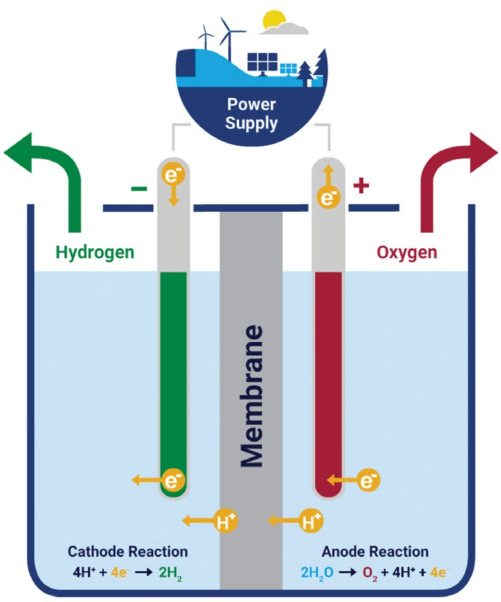
There are different types of electrolysers that support a wide range of solutions based on cost, capacity and application. The two main types include alkaline and PEM technologies.

## 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)[22].

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[26].



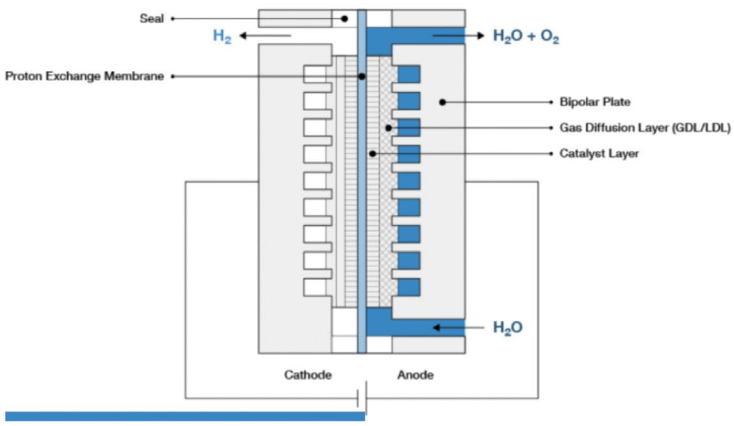

Alkaline electrolysis (Cummins.com)

## 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 to them/gases away from them, conduct electricity, and circulate a coolant fluid to cool down the process[26].




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)[27].
- However, PEMs are often seen as a safer option since the membrane provides a physical barrier between the produced $H_2$ and $O_2$.
- 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.
- And further, PEM is also a more compact machine which is better suited with renewables as they can operate dynamically using varying loads of electricity[28], 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[29].

The world's largest electrolyser in operation today is a 20MW PEM unit in Bécancour by Air Liquide[30]. This has the capacity to produce over 8.2 metric tons of low-carbon hydrogen per day. However, industrial gas giant Linde plans to build a 24MW PEM electrolyser at Leuna in Germany by the second half of 2022[31]. And also, energy giants Total and Engie have recently announced plans to build a 40MW electrolyser using 100MW of PV power at a refinery in Southern France[32]. The plant is slated to be operational in 2024, and theoretically is stated to be able to produce up to 15 tonnes of green hydrogen per year.

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[33].

| $H_2$ Production | Output Pressure | Water Consumption | $H_2$ Purity | Power Requirement Per Hour | Input Voltage | Technology Used | Lifespan Hrs Continuous Use |
|---|---|---|---|---|---|---|---|
| Inm3/hr | 30bar (437psi) | 0.81/hr | 99.940% | 4kW | AC (240V) or DC | AES | 10000 |
| 2nm3/hr | 30bar (437psi) | 1.61/hr | 99.940% | 8kW | AC (240V) or DC | AES | 10000 |
| Inm3/hr | 0-7.9bar (0-115psi) | 11/hr | 99.998% | 6.7kw | AC (240V) or DC | PEM | 30000 |
| 2nm3/hr | 0-7.9bar (0-115psi) | 21/hr | 99.998% | 13.4kW | AC (240V) or DC | PEM | 30000 |
| 10nm3/hr | 4-10bar (58-146psi) | 15-20l/hr | 99.998% | 54kW | 3phase AC | IMET | 60000 |
| 15nm3/hr | 4-10bar (58-146psi) | 22.5-30l/hr | 99.998% | 81kW | 3phase AC | IMET | 60000 |
| 30nm3/hr | 4-10bar (58-146psi) | 45-60l/hr | 99.998% | 156kW | 3phase AC | IMET | 60000 |
| 45nm3/hr | 4-10bar (58-146psi) | 67.5-90l/hr | 99.998% | 234kW | 3phase AC | IMET | 60000 |
| 60nm3/hr | 4-10bar (58-146psi) | 90-120l/hr | 99.998% | 312kW | 3phase AC | IMET | 60000 |
| 220nm3/hr | 4-10bar (58-146psi) | 200-220l/hr | 99.998% | 1MW | 3phase AC | PEM | 60000 |

Hydrogen production vs water consumption, purity and power required (covertelpower.com.au)

# 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, transport and compression of the gas[34].

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.

## 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[35]. This means lower average costs of generating electricity over the lifetime of assets, which is expected to continue as the energy transition to renewables endures.

The levelised cost of electricity LCOE (measure of average electricity generation costs over the lifetime of a generating plant) for large scale solar PV installations in 2020 was A$41-77/MWh internationally[36]. The equivalent numbers for onshore wind were A $56-93/MWh[36].

The mean cost projection for 2030 across both PV and onshore wind is A$40/MWh, and the lowest estimate was A$25/MWh[37].

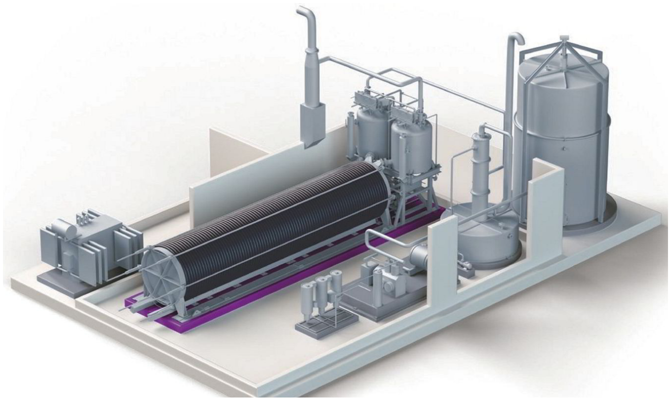
It is also important to note that for an electrolyser to operate at its highest capital efficiency, this will require the input of firm renewable energy to mitigate the risk of unpredictable $H_2$ production volumes impacted by variables such as weather.

## COST OF ELECTROLYSERS

The IEA estimates alkaline electrolysers between A$714-2000/kW (today) and A$571-1214/kW (2030). With PEM electrolysers between A$1571-2571/kW (today) and A$928-2143/kW (2030)[38].

It is estimated that Chinese electrolyser manufacturers sell alkaline technology at ≈A$262/kW – or roughly 80% cheaper than European machines of the same type due to economies of scale[39].

And furthermore, the electrolyser industry has dropped its capital costs by ≈75% in the past 4 years, driven mainly by market need for larger systems and innovation in system design and manufacturing. Costs of hydrogen electrolysis capex is expected to drop by a further 30-50% in the next decade, as national targets and pilot projects produce enough volume to realise substantial declines.

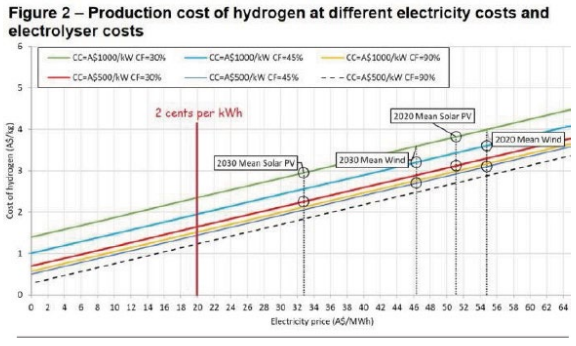


Hydrogen electrolyser sample diagram (rechargenews.com)

Overall, current hydrogen production costs range from ≈ A$4.78-7.43/kg. However, with CSIRO projections in conjunction with forecasted electricity costs, resultant hydrogen production is estimated at A$1.89-3.71/kg for 2030[40].

Siemens Energy recently announced plans to produce green hydrogen at US$1.50/kg (≈A$2/kg) by 2025 "based on large-scale commercial projects in operation"[41]. 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 at 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, but 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.

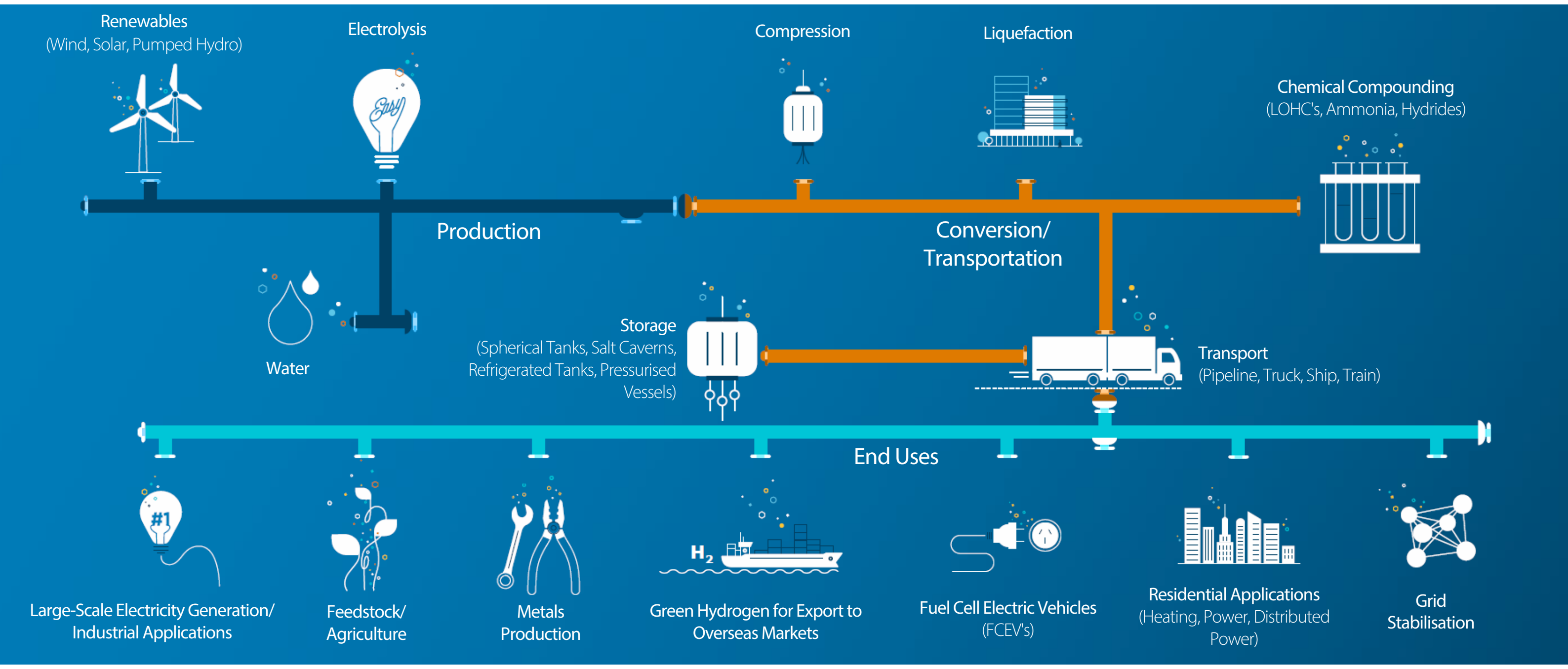



Cost of hydrogen vs. electricity price at different capacity factors (energy.anu.edu.au)

# CONSUMERS

- Industrial Feedstock
  - Hydrogen feed for various industrial processes to produce an end product, such as ammonium nitrate
- Gas Blending
  - Hydrogen for power to gas for energy storage in large scale gas supply piping networks
- Grid Stabilisation
  - Hydrogen for use in stationary power generation for grid stabilisation – optimising power from base load for the power utility industry
- Mobility
  - Hydrogen for use in fuel cell powered transport and other mobility applications including maritime, light and heavy vehicle
- Distributed Power
  - Hydrogen for use in stationary power generation microgrids for the power utility industry and industrial sites
- Green Hydrogen Access (Export)
  - Access to green hydrogen into various overseas markets with different carrier streams (H, NH3 or liquid)
- Future Markets
  - There is also un-tapped additional scope to capture oxygen produced from the electrolysis process and sell to buyers for a wide variety of applications

# THE GREEN HYDROGEN VALUE CHAIN



# CHALLENGES

## MATURITY

Although the technology is decades old, 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.

## COSTS

The major goal for electrolyser providers is to achieve "fossil parity", meaning electrolyser produced green hydrogen costs the same as using steam methane reforming (SMR) with natural gas or coal (grey and brown hydrogen, respectively). By comparison, green hydrogen is currently 2.5 times as expensive as generating blue hydrogen (SMR with carbon capture and storage)[42], however this is diminishing with rise in demand.

Manufacturers are working hard to reduce the costs of components within electrolysers, with product standardisation and repeat parts being used helping to achieve such. Furthermore, to ramp up electrolysers to gigawatt scale, manufacturing in higher- throughput continuous processes, such as roll-to-roll, as well as high-speed inspection over large-area components to find defects that could impact durability is also being looked into (as opposed to batch process manufacturing). 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 which is discussed further in the following paper on hydrogen transportation and mobility.

Transport costs vary greatly dependent on the method used and 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

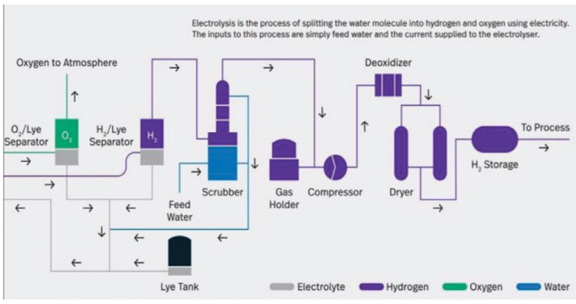
Hydrogen electrolysis specifically requires de-ionised water to be used as an input to production, however feedwater quality is currently an emerging area of research from manufacturers. Early-stage projects are investigating the ability to use dirty water or salt water as an input, as opposed to requiring high-purity water for electrolysis.

The cost of this input can be significant and therefore is an important factor to consider. Bulk de-ionised water costs are ~A$0.05- 0.15 per litre. To put that into perspective, an electrolyser that produces 1Nm$^3$/h will use roughly 1L/h, so a standard size electrolyser of 2000Nm$^3$/h could cost up to ~A$99-298 for water per hour.

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 KOH 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 a high purity of 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)[43]. 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 electrolysers[43].

# MAJOR MANUFACTURERS

| Company *(non-exhaustive list)* | Country | ALKA- LINE | PEM | AEM |
|---|---|---|---|---|
| Cummins Inc (Hydrogenics) | Germany, Belgium, USA | X | X | |
| ITM Power PLC | UK | | X | |
| Giner ELX Inc | USA | | X | |
| NelHydrogen (Nel ASA) | USA, Norway | X | X | |
| Enapter srl | Italy | | | X |
| Areva H2Gen Gmbh Elogen | Germany, France | | X | |
| Green H2 systems/A company of Fest Group (H-Tec Systems Gmbh iGas energy Gmbh) | Germany | | X | |
| Green Hydrogen.dk | Denmark | X | | |
| IPS-FEST Gmbh | Germany | X | | |
| Kraftanlagen Munchen Gmbh | Germany | X | X | |
| Thyssenkrupp Uhde Chlorine Engineers Gmbh | Germany | X | | |
| Hoeller Electrolyzer Gmbh | Germany | | X | |
| Siemens | Germany | | X | |
| HyGear | Netherlands | X | | |
| McPhy | France | | | |
| PERIC | China | X | | |
| Suzhou Jingli Hydrogen | China | X | | |
| CETH2 | France | | X | |

## JURISDICTIONS

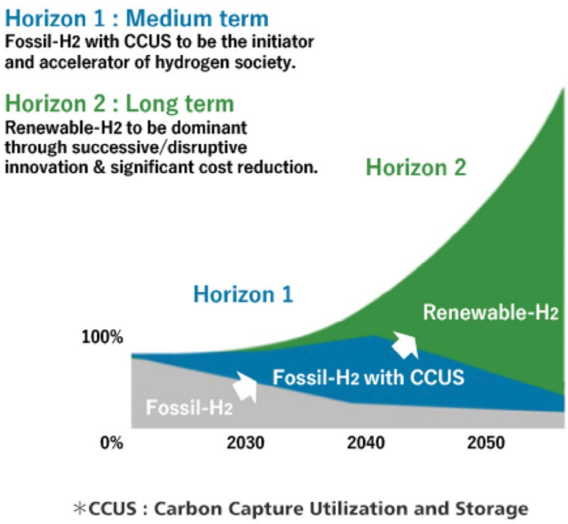
China currently dominates the global market for alkaline electrolysers, with PEM technologies occupying less than 10% of the market share[44]. However, many European-based companies are also leading the way on developing innovative technologies that better suit the production of green hydrogen through 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)[45], this outlook shows continued promising growth for the jurisdiction.

Germany, specifically, is a significant player in hydrogen electrolyser manufacturing field, with many of the aforementioned major manufacturers listed being German-based.

And 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.

# CONCLUSION

For storing and shifting large amounts of renewable energy, hydrogen represents the cleanest and most flexible solution. The key trend in the market is the interconnection of declining renewable energy costs with lower cost electrolyser technology, to produce green hydrogen at prices that can be competitive with fossil fuel-based hydrogen. This is expected to be achieved by 2030, however it remains unclear if renewable power prices will fall fast enough to produce competitive green hydrogen.




Expectations on hydrogen energy (power.mhi.com)

With public demand for climate action, policy pushes to find green gas solutions, and businesses racing to display green credentials, hydrogen has increasingly become a key focus area for helping companies achieve pathways to net zero carbon emissions, bringing environmental sustainability to the fore. From 2000-2019, a total of 252MW of green hydrogen electrolysers were deployed[46]. And by 2025, an additional 3,205MW of electrolysers dedicated to green hydrogen production are expected to be deployed globally (a 1,172% increase)[46].

Increased government and policy support has been realised around the world, with Australia's release of a national hydrogen strategy in late 2019, and a plethora of other countries plus the EU having also published hydrogen strategies of there own in recent years. In Australia, many projects, pilots and feasibility studies are under way, many co-founded or funded by ARENA (the Australian Renewable Energy Agency) which has already committed A$60 million across 2012-2021 to accelerate the development of green hydrogen, and approved a further A$103 million in 2020-21 to fund three projects that will build and operate some of the world's largest hydrogen electrolysers[47].

Hydrogen electrolyser technology is market proven and continues to advance. It is also expected that fuel costs per kilogram of hydrogen will fall as distribution and retail infrastructure scale up. This seems quite reasonable given the significant cost reductions already achieved in the last decade. And it is categorically on course to be cheaper than producing hydrogen from natural gas or coal with carbon capture and storage in the future.

# HYDROGEN TRANSPORTATION & MOBILITY

## INSIDE




Research Paper
Author:
**Jessica Paterson**

# EXECUTIVE SUMMARY

## OVERVIEW

- Hydrogen is experiencing unprecedented momentum and is becoming an increasingly important part of our clean and secure energy future. 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 vs the combined cost of production and transportation, especially as the volume, investments and demand for hydrogen rise into the future.
- Australia is uniquely positioned in the global market to become a leader in clean hydrogen. 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 $H_2$ over the brink into full commercial scale development.
- Hydrogens applications in the mobility sector span a multitude of uses including passenger and heavy-duty vehicles, material handling equipment, aviation and maritime.
- The Hydrogen Council forecasts that by 2050, hydrogen could power more than 400 million cars, 20 million trucks, and ~5 million buses, which constitute on average 20-25% of their respective transportation segments[48].

# POLICY

Australia is already a significant energy exporter to Asia, and a large proportion of Australia's top trading partners have already committed to using clean hydrogen to decarbonise their energy systems. This presents an excellent opportunity for Australia to become a global leader in the emerging hydrogen industry.

Australia has already entered, or plans to enter, into a number of bilateral agreements with trading partners to promote trade and investment in hydrogen, including with[49]:

- **Japan** – Partnership on de-carbonisation through technology (2021); Joint Statement on Cooperation on Hydrogen and Fuel Cells, and continuation of the HySTRA project (2020)
- **Singapore** – A$30 million partnership to accelerate the deployment of low emissions fuels and technologies like clean hydrogen in maritime and port operations (2021) and a Memorandum of Understanding (MoU) to collaborate on Low Emissions Solutions (2020)
- **Germany** – Investing in new hydrogen initiatives together including a Joint Declaration of Intent on the Australia-Germany Hydrogen Accord to create new economic opportunities, whilst reducing emissions (2021) and the HyGATE hydrogen project incubator co-led by the ARENA
- **United Kingdom** – Letter of Intent to establish a parternship cooperating on R&D across low emissions technologies, including clean hydrogen, to increase global scalability (2021)
- **Republic of Korea** – Partnership on Low and Zero Emissions Technology, including a focus on clean hydrogen deals (2021)
- **US** – US, Australia, Japan and India established a Clean-Hydrogen Partnership at the Quad Leaders' Summit (2021) and Australia became a member of the US Centre for Hydrogen Safety (2019)
- **Canada** – MoU between the Canadian Hydrogen and Fuel Cell Association (CHFCA) and the Australian Hydrogen Council (AHC) to collaborate on the commercial deployment of zero emission hydrogen and fuel cell technologies (2020)

In addition to this, industry and government policy initiatives are being developed at pace from multiple sources. Statements such as the National Hydrogen Strategy, Low Emission Technology report and the State of Hydrogen 2021 which outlines the country's progress so far are the clearest indications that the Federal government is committed to advancing hydrogen based economic growth. In support of this, all Australian states and territories have also released green hydrogen strategies which signal support for hydrogen developments.

As an industry development indicator, recent reports estimate the Australian private sector investment to have committed in excess of A$1.6 billion, with the Australian public sector investment also having committed over A$1.27 billion as at Jun 2021[50]. Industry and research institutions such as the ARENA, CEFC and AHC are assisting in making major headway in progress clean hydrogen projects. This includes the funding of regional hubs, feasibility studies, pilot projects and research programs.

The 2021-2022 Federal Budget also announced a A$275.5 million investment to accelerate the development of clean hydrogen export hubs, increasing the Government's commitment to building an Australian hydrogen industry to A$1.2 billion[49,51].

# 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/m$^3$) poses inordinate 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 in order 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.

| Conversion Method | Density | Cost (A$) |
|---|---|---|
| Compression | 40kg/m$^3$ (700 bar) | +$0.9/kg |
| Liquefaction | 70kg/m$^3$ (1 bar) | +$4.1/kg |
| LOHC | 47-57kg/m$^3$ | +$1.7/kg |
| Ammonia | 123kg/m$^3$ (10 bar) | + $2.6/kg |

Density and cost of conversion methods (deloitte.com)

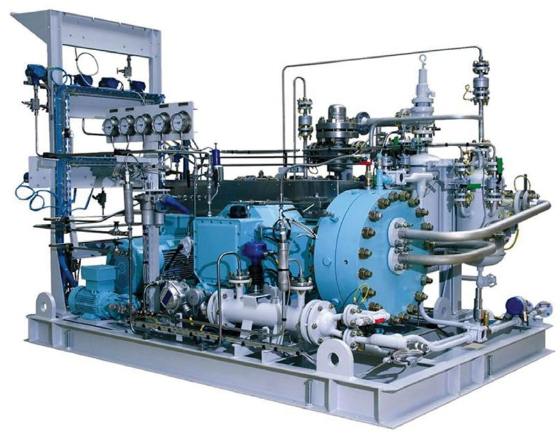
## COMPRESSION

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[53].

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



Hydrogen compressor machine (neuman-esser.de)

There are 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[54]. 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.

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.

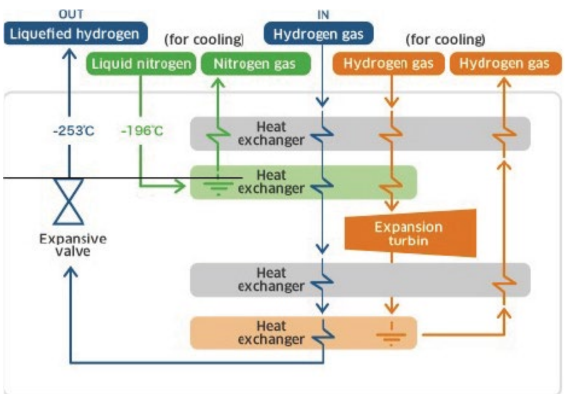
This issue of permeation losses is also faced within compressed $H_2$ tube trailers. Due to their still comparatively quite low volumetric energy density, trailers are only commercially available for small distances and for capacities of a maximum amount of 300kg[55]. This highly limits the viability 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. Compression adds an average of $0.9/kg to the cost. By comparison, LOHC adds $1.7/kg, ammonia adds $2.6/kg, and liquefaction adds $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 difference that liquefaction makes on the volumetric density of $H_2$ is a reduction to 1800th of the amount of space that gaseous $H_2$ would occupy. By way of comparison, LNG's boiling point is at -161°C, and its liquefaction volume takes up 1600th of the state required in that of gas.




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[56]. 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[57].

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[58]. PDBT has a volumetric hydrogen storage density of 57kg/m$^3$, and MCH has 47kg/m$^3$.

Making LOHCs involves storing $H_2$ in a chemical bonded form through reversible, catalytic hydrogenation[58]. For reconversion at delivery, a $H_2$ release unit (i.e. chemical reactor for dehydrogenation) is also required. The major advantage of LOHCs are 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[56]. 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 costs of reaching final users. However, because of its toxicity it requires handling by certified personnel only, possibly restricting its techno-economic potential[58]. 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.

Similar to that of 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.

Producing ammonia is typically obtained on a large-scale by the Haber-Bosch process which combines $H_2$ and nitrogen together directly through synthesis[58]. 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 following segments. It is assumed that pipelines store $H_2$ in salt caverns, $LH_2$ in large spherical tanks, ammonia in large refrigerated tanks, and compressed $H_2$ in pressurised vessels.

| Transport Method | CAPEX (A$) | Cost (A$/kg$H_2$/50km) |
|---|---|---|
| Pipeline | $1.03-1.55M/km | +$0.1-0.3 |
| Truck | CGH2 $0.96M<br>LH2 $1.39M | CGH2 +$1.05<br>LH2 +$5.95 |
| Ship | $310-533M | NH3 +$0.02<br>LH2 +$0.05 |

Cost of transportation methods

## PIPELINE

Hydrogen can be transported in pipelines in two ways.

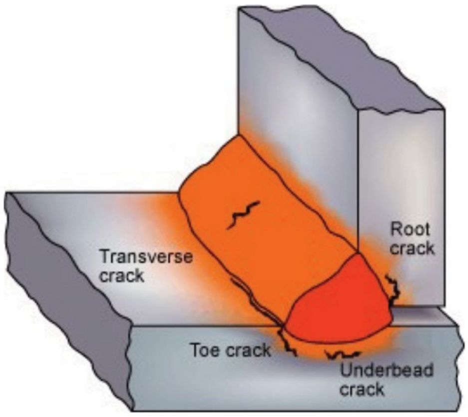
1. Blended into existing natural gas pipelines
2. Building new specialised $H_2$ pipelines.

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)[59]. 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. It is expected that 5-20% $H_2$ by volume can be mixed into existing natural gas systems, without the need for end-use appliance retrofit/ replacement or major gas network upgrades[59]. The blending limit depends on the physical compatibility of the existing gas distribution network and appliances, as well as regulations. If natural gas was blended with 20% of renewable $H_2$, this would reduce $CO_2$ emissions from combustion by 7%. The relationship is non-linear due to differences in densities, and so a larger volume is needed to deliver the same amount of energy.

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[60]. 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[60]. 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%[61].

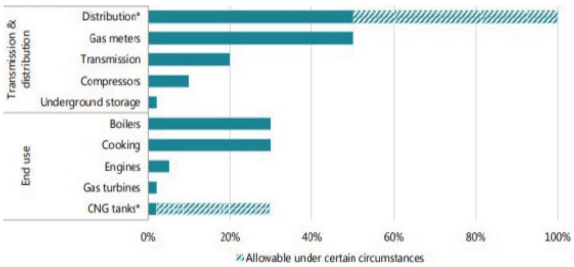
Another alternative is to line steel pipelines with internal plastic coating, or the conversion into ammonia which avoids embrittlement. It is suggested that utilising $H_2$ within existing infrastructure may be up to 40% less expensive than full electrification of a gas network. However, this is somewhat 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"[62]. 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 a number of 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[63]. 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.




Tolerance of existing elements of the natural gas network to hydrogen blend percentages (IEA.org)

Another challenge faced in pipeline usage is that 3x 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 in order to maintain pressure.

However, these figures do not take into account 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[64].

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 1,100kg$H_2$ (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 4000kg$H_2$ 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 translat es 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.

| Type | Truck Cost (A$) | Capacity | OPEX (per 50km) |
|---|---|---|---|
| **$CGH_2$** | ~$960,000 | 700kg/$H_2$ | $1.05/kg |
| **$LH_2$** | ~$1,390,000 | 4,400kg/$H_2$ | $5.95/kg |

Cost comparisons across trailer types

## 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 $LH_2$ 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. Studies for the shipping of ammonia, LOHCs and compressed hydrogen are also underway.

Shipping tankers could be facilitated through the use of 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 1,250$m^3$ [65]. The HySTRA consortium plan to scale up capacity after the achievement of successful initial voyages. By comparison, standard ocean LNG vessels are around 350m long, and have holding capacities of up to 260,000$m^3$. 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. Aus → Japan) the ship faces around 0.2-3.2% boil-off per day. For an $LH_2$ voyage, this is expected to be around 5-10% per day[56]. 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 the fact that unless a high-value liquid can be transported in the opposite direction in the same vessel, ships would need to return empty. Similar to 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. Speculations suggest $H_2$ ships to cost greater than that of 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 to cost up to A$533 million[66].

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-user which can alter the price competitiveness greatly.

### 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)[67]. 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.

# MOBILITY

Many countries have already announced their intention to phase-out thermal internal combustion engines (ICE in the near future. Hydrogen mobility could therefore become part of the solution and it is expected that by 2050, 113 million fuel-cell electric vehicles (FCEV could be on the road[68]. This occurrence would save up to 68 million tonnes of fuel and almost 200 million tonnes of carbon emissions[69], making a significant contribution to reducing energy consumption and GHG emissions within the transport sector.

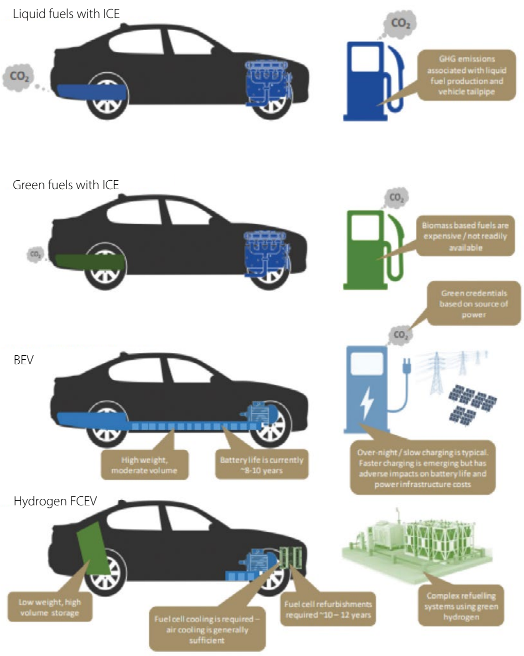
$H_2$ can be used in fuel cells to efficiently generate electricity for an electric vehicle, or can be converted into a denser form (such as ammonia, methanol and synthetic fuel for use in ICEs. Unlike in some sectors, $H_2$ already has a decarbonised competitor in lithium-ion batteries. Battery costs have fallen by ~80% in the last decade[70], helping to spur demand and increase total market share for battery electric vehicles (BEV. Hydrogen FCEVs, by comparison, are currently a more expensive alternative, and mostly still in the prototype/small demonstration phases only.

The $H_2$ mobility sector spans a number of end-uses for FCEV's including light passenger vehicles, buses, heavy-duty trucks, material handling, ferries, marine shipping, aviation, and other associated infrastructure such as refuelling stations.

At the current stage in time, the CEFC has found only remote power, line-haul, material handling and return-to-base vehicles (incl. buses) to be presently commercially viable[5]. All others suggest a need for increased end- user efficiency, reduced transport and dispensing costs or lower $H_2$ supply costs to become competitive with battery or fossil-fuel alternatives.

To further unlock the full potential of $H_2$ mobility applications, an integrated approach will be required including increased policy support (either through quantitative targets for a vehicle type or specific funding for mobility applications being made available), full supply chain coordination between $H_2$ production to refuelling infrastructure provider, 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)

EV's 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 is the reverse of an electrolysis procedure, and the cell stack includes a $H_2$ storage tank pressurised to 700 bar[71]. Fuel cells are preferable as they are quiet, are emissions free, and are 2-3x more efficient than traditional combustion technologies[72]. Furthermore, FCEVs compete against BEV's in the fact that they are more suitable for consumers who travel longer distances (i.e. 400-600km without refuelling), have faster refuelling times, lower final investment costs, and space requirements of up to 15x less than BEVs.

**Safety:**

By their nature, all fuels have some degree of danger associated with them. However, a number of $H_2$'s properties make it safer to handle and use in comparison to other commonly used fuels. $H_2$ is non-toxic, and due to its light density it dissipates quickly when released, allowing for relatively rapid dispersal in the case of a leak[73].

The manufacturing of fuel cells require additional engineering controls to ensure their safe use. This is primarily aimed at mitigating flammability risk. And as such, adequate ventilation alongside flame detectors, tank leak tests, garage leak simulations, and hydrogen tank drop tests are standard in the design of safe $H_2$ systems[74]. FCEV's themselves have arrays of $H_2$ sensors that sound alarms, and seal valves and fuel lines in case of leaks. The pressurised tanks that store the $H_2$ have also been found to be safe in collisions throughout repeated testing.

Furthermore, $H_2$'s vapours 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 the ground in well-ventilated areas.

## LIGHT VEHICLES

According to Budget Direct statistics, a typical Australian car uses ~10.8L/100km (353MJ/100km) of petrol with a total dispensed fuel cost of A$2,030/year (A$1.40/L). If this was replaced by an equivalent $H_2$ FCEV using 0.8kg/100km (107MJ/100km), the dispensed fuel cost would be A$1,608/year (A$15/kg)[5]. $H_2$'s fuel consumption, by comparison due to its energy density, clearly outcompetes diesel with 1kg of hydrogen containing approximately the same energy as a gallon of diesel[75].

However, taking into account the total cost of ownership of the $H_2$ FCEV compared to that of an ICE, the result is the relative competitiveness of -A$16.54/kg[5]. This shows that the light vehicle sector is currently not commercially viable for the adoption of $H_2$. However, as technology and demand for low carbon vehicles improve, this economic gap will steadily decline into the future.

The light vehicle sector is forecast to achieve parity with ICE technology over time as the cost of delivered petrol increases and the cost of FCEVs and $H_2$ decreases. FCEVs can achieve a much higher fuel efficiency than ICE, and to drive their competiveness a significant uptake of FCEVs will be needed to justify the expense of $H_2$ refuelling stations.

The average travel range of current passenger FCEV's is 400+km (BEVs: ~250km)[76]. However, the Toyota Mirai recently made a record distance of 1360km in one tank (consuming 5.45kg of $H_2$ over two days)[77]. The current main leaders in light FCEV manufacturing include Toyota and Hyundai, both of which have recently announced ambitious targets around $H_2$ FCEV annual production capacities.

## MATERIAL HANDLING

FCEVs are already seeing a fast uptake in the materials 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, also is removed with FCEVs.

The most common materials handling FCEV is that of forklifts, in which $H_2$ is able to power up to 2,500kg of lift capacity. The 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 8 hours to recharge.

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


Hydrogen fuel cell forklifts by Toyota (left) and Hyundai (right) (h2-view.com)

## HEAVY-DUTY VEHICLES

Although $H_2$ hasn't taken off in the automotive industry as of yet, several established manufacturers (including Hyundai, Scania, Toyota, Volkswagen and Daimler, among others) are understanding the potential that FCEVs can have in the heavy-duty transport sector to make commercial vehicles greener.

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. For this reason, it is forecasted that $H_2$ will outcompete diesel in the heavy-duty vehicle division before 2030, demonstrating $H_2$s potential for expansion throughout the mobility sector.

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 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 an important consideration for long-haul trucks subject to weight penalty policies.

## OTHER

**Rail:**

With only 10% of Australia's railway tracks currently electrified[78], $H_2$ powered rail could have a place in future infrastructure considerations. $H_2$ fuel cell locomotives are currently under development, building on the passenger rail demonstration projects in Germany (such as the Alstom iLint unit). With rail FCEVs having the opportunity to be comparable in cost with that of electrification, $H_2$ technology is most competitive for services requiring long distance movement of large trains with low-frequency network utilisation, or cross-border freight. 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. Use of hydrogen derived fuels, such as ammonia and methanol, will require reciprocating engine technology until such time as 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 and represents an opportunity for $H_2$-based fuels. Pure hydrogen-powered marine passenger ships are gradually emerging to combat air and water quality issues. Maritime freight is also set to grow exponentially by 2030, providing an incentive for the sector to transition into the use of $H_2$ fuel cells to facilitate transportation.

**Aviation:**

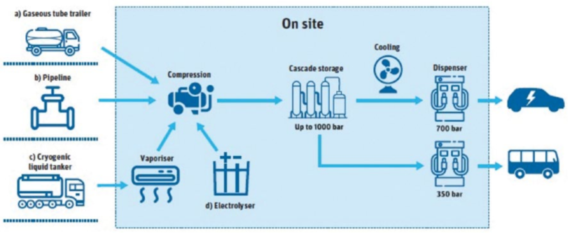
There is significant pressure on the airline sector to decarbonise in order to retain its social license to operate. The industry is actively seeking commercially viable carbon intensity reduction solutions, therefore also presenting an opportunity for $H_2$. Similar to that of maritime uses, fuel cells are also beginning to be adopted by Unmanned Aerial Vehicles (UAV) or drones to power propulsion mechanisms. Fuel cells can provide 8-10x more flight time in some UAV models and have shorter refuelling times than batteries[79].

In terms of manned aircraft/passenger aviation, fuel cell application to this sector appears to be currently quite distant. The potential of using $LH_2$ and synthetic aviation fuel is only viable for regional flights (20-80pax, within a 1000km range) whilst using electrically driven turbo props[80]. However, longer haul flights are likely to still use jet engines fuelled by sustainable aviation fuels.

Green $H_2$ has also recently been used in Australia as rocket fuel to launch re-useable satellites carrying payloads into lower earth orbit. This project is being developed through a partnership between QLD-based Hypersonix Launch Systems and BOC, and demonstrates the versatility of $H_2$ as a fuel source.

## REFUELLING STATIONS

Hydrogen refuelling stations (HRS) consist of a standard overall system that can vary in hydrogen delivery method, dispenser pressure, and capacity, which consequently affect their configuration and costs. The $H_2$ is delivered in gaseous form, which is compressed for intermediate storage. And control systems are necessary to monitor volume, temperature, flow rate, and pressure, all of which require high electricity levels to regulate. Current dispenser nozzles cost up to 100x more than the petrol equivalent[53], however the installation of $H_2$ refuelling infrastructure, has picked up momentum significantly in the past few years.




A standard refuelling station configuration (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 that of 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 at least 10,000 fast-charging public stations and 1m private charging stations that would be required for BEVs[81].

For a fully developed infrastructure, ~3000 FCEVs per station are expected. With higher ratios of cars to refuelling stations implying better co-ordination between vehicle and infrastructure deployment, therefore leading to lower $H_2$ prices.


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

The infrastructure to support $H_2$ powered vehicles in Australia is on its way as the technology becomes more widespread, and the demand low-emissions technology ramps up. Neoen and ActewAGL opened Australia's first $H_2$ vehicle-refuelling station in Canberra, marking a major milestone in the roll-out of FCEVs. The ACT Government will use the station to service the state Governments new fleet of Hyundai Nexo $H_2$ cars, as they transition to a 100% zero- emissions passenger fleet. It can produce 22kg$H_2$/day and store 50kg. There is also the Toyota Hydrogen Center in Melbourne, and two other new refuelling stations in the pipeline to open shortly which will produce up to 50kg - 80kg$H_2$/day.

## COSTS

Transport, storage, handling and dispensing all add costs. Currently, $H_2$ at specialised vehicle refuelling stations costs around ~A$14/kg[5]. This would need to fall substantively to achieve parity with gasoline.

The cost competitiveness of direct hydrogen use in FCEV's depends on how three critical cost components develop compared with their present and potential future competitors:

1. **The cost of the fuel cell stack**

   The current commercial cost of a typical fuel cell is estimated to be ~A$300/kW[38]. However, research into technological advancements and cost component reduction is aiming to bring this amount down, especially as manufacturing of cell stacks benefits from economies of scale.

   R&D activities suggest that it may be possible to increase catalyst activity of the cell stack and thus reduce/eliminate the platinum content (one of its most expensive components). 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 the fuel cell, and it is expected to reduce by ~23% to A$230/kW in the coming decades.

2. **The cost of on-board storage**

   On-board storage of $H_2$ requires it to be compressed at 350–700 bar for cars/trucks, and this uses the equivalent of 6-15% of the $H_2$ energy content.

   The costs of current on-board storage systems (including fittings, valves and regulators) are estimated at A$30/kWh of useable $H_2$ storage, at a scale of 10,000units/year[38]. If this were to scale up to 500,000units/year, costs would benefit by decreasing to A$18–24/kWh over time.

3. **The cost of refuelling**

   Investment costs for $H_2$ refuelling stations are estimated to be in the range of A$776,000–2,600,000 for $H_2$ at a pressure of 700 bar (and A$194,000–2,070,000 at 350 bar)[38]. The lower end of these ranges are for stations with a capacity of 50kg$H_2$/day while the upper is for 1,300kg$H_2$/day. The two largest cost components are the compressor (which can make up to 60% of the total cost), and storage tanks (which are relatively large due to $H_2$s low density). Similar to that of the cell stack and on-board storage, refuelling stations would benefit greatly from the building of economies of scale. The future increase in capacity from 50kg$H_2$/day to 500kg$H_2$/day would reduce refuelling stations costs by up to 75%.

# MAJOR MANUFACTURERS

| Category | Company *(non-exhaustive list)* | | | |
|---|---|---|---|---|
| Compression | - Mehrer<br>- LW Compressors<br>- PDC<br>- Flowserve | - Sauer Compressors<br>- NEA Compressors<br>- RIX | - Nash<br>- Toplong Compressors | - Adicomp<br>- Brotie<br>- Howden |
| Liquefiers | - Protium Innovations LLC | - Kawasaki<br>- Linde | - Air Liquide | - Metavista |
| LOHC Technologies | - Hydrogenious | - Hynertech | | |
| Cooling Systems | - KUSTEC Kalte-Und System Technik GbmG | - Sterling Thermal Technology | - Ansaldo Energia | |
| Storage | - GKN Hydrogen<br>- Hydrexia<br>- Svante | - Hexagon Purus<br>- Hydrogenious<br>- LAVO | - Kessels<br>- Reuther<br>- HPS | - NPROXX<br>- Worthington Industries |
| Trailer Manufacturers | - Calvera<br>- Chart | - Weldship Corporation | - Linde<br>- Wystrah | - CIMC ENRIC |
| Fuel Cell | - ULEMCo<br>- Plug Power<br>- NPROXX | - SFC Energy<br>- WS Reformer GmbH | - Quantum Fuel Systems<br>- Fuelcellenergy | - Aeristech<br>- CryoStar |
| Mobility | - Nikola Motor Company<br>- Hyzon | - Honda<br>- Toyota<br>- Scania | - Volkswagen<br>- RG H2<br>- PSA Groupe | - Daimler<br>- Air Liquide<br>- Hyundai |

# CONCLUSION

The realisation of a vibrant $H_2$ transport and mobility economy will require early intervention and significant Government investment. Australia's opportunity to gain comparative advantage requires progressive development in both the domestic end-use market, as well as in international exports, to drive wider advancements within the industry. This will support the social licence of $H_2$ and add greatly to the country's decarbonisation efforts.

The phase out of fossil fuels and assessment of common user infrastructure (such as $H_2$ suitable pipelines, and ports that can facilitate liquefaction/compression needs), will also be imperative in building the viability of a $H_2$ transportation economy.

$H_2$ FCEVs have great potential to drive the future of mobility, with fuel cell technology showing the potential to become on-par or even more cost-effective than that of its BEV or ICE competitors over time in a variety of commercial applications.

Therefore Governments, businesses and energy consumers must continue to align on the need for net-zero emissions, with a consistent policy and regulatory environment encouraging innovation to help build economies of scale and attract further hydrogen investment into the future.

# CARBON CAPTURE & STORAGE

## INSIDE



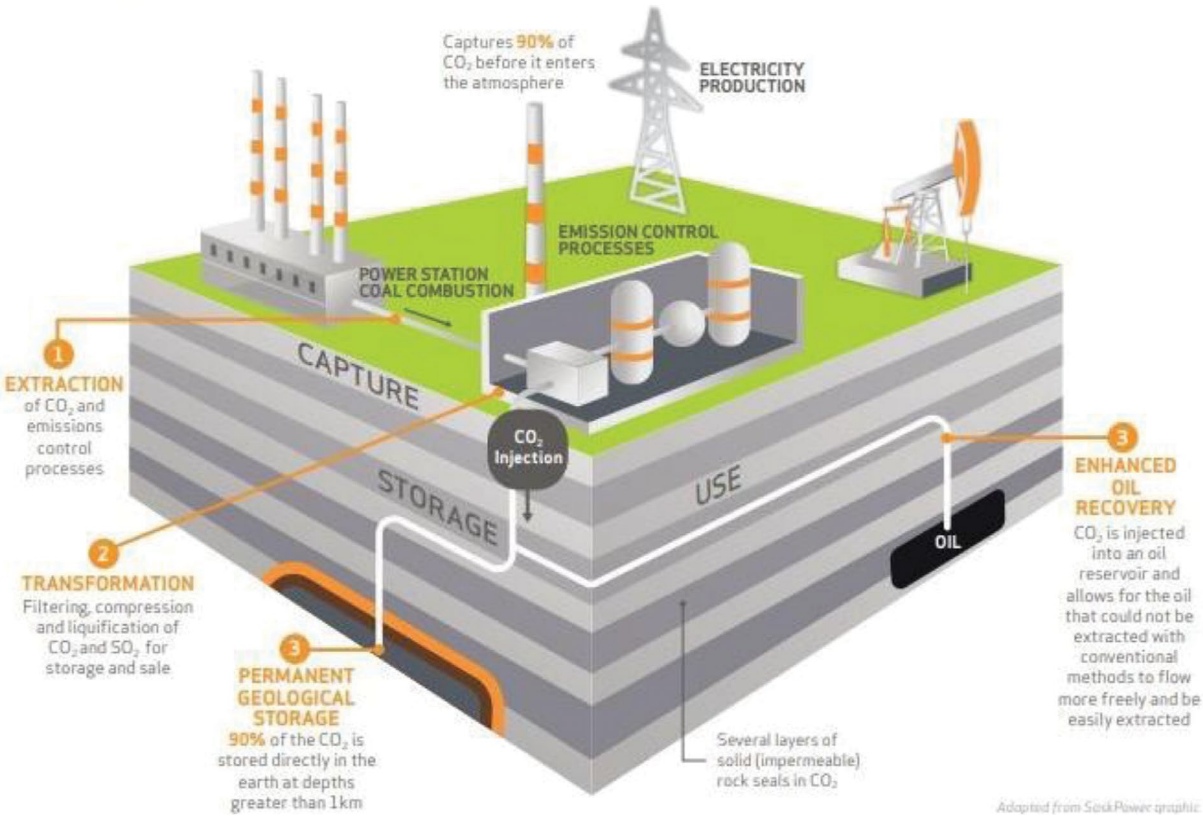
Research Paper


Author:
**Maggie Cai**

# CHAPTER 1:
# CARBON CAPTURE AND STORAGE

## WHAT IS 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[82]:
  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.
  3. STORAGE - $CO_2$ is injected into deep underground rock formations, often at depths of one kilometre or more.
- The Global CCS Institute estimates as much as **14,000 gigatons of storage potential**, equivalent to over 379 years of 2018-level annual emission.
- $CO_2$ can be stored in oil and gas reservoirs, un-mineable coal seams and saline reservoirs.




Sample CCS process flow diagram (saskpower.com)

## THREE PRIMARY CARBON CAPTURE SYSTEMS

**There are three primary carbon capture systems:** Pre-combustion, post-combustion and oxy-combustion[83]. **Post-combustion capture** for power plants is the most common CCS technology and application. These projects most frequently use amine-based solvents to remove $CO_2$ from flue gas.

| Carbon Capture System | Description |
|---|---|
| Pre-combustion | Pre-combustion processes convert fuel into a gaseous mixture of hydrogen and $CO_2$. The hydrogen is separated and can be burnt without producing any $CO_2$; the $CO_2$ can then be compressed for transport and storage. The fuel conversion steps required for pre-combustion are more complex than the processes involved in post- combustion, making the technology more difficult to apply to existing power plants. |
| Post-combustion | Post-combustion processes separate $CO_2$ from combustion exhaust gases. $CO_2$ can be captured using a liquid solvent or other separation methods. In an absorption-based approach, once absorbed by the solvent, the $CO_2$ is released by heating to form a high purity $CO_2$ stream. This technology is widely used to capture $CO_2$ for use in the food and beverage industry. |
| Oxy-combustion | Oxy-fuel combustion processes use oxygen rather than air for combustion of fuel. This pro-duces exhaust gas that is mainly water vapour and $CO_2$ that can be easily separated to produce a high purity $CO_2$ stream. |

## CCS: POLICIES

- Several large economies have committed to supporting CCS in order to meet climate goals.
  - The Intergovernmental Panel on Climate Change (IPCC) and International Energy Agency (IEA) have both evidenced the critical role that CCS must play in meeting global emissions reduction goals.
  - The UNECE developed recommendations on CCS and on carbon capture, utilisation and storage (CCUS), which were endorsed by its 56 member States in November 2014.
- However, only a handful of markets provide direct support for project deployments.
- Locally, both Australia's state and federal government have been major contributors to CCS R&D.
- The Morrison Government in May 2020, accepted the recommendations in the King Review, which includes amended legislation to enable development of a CCS method within the A$2 billion Emissions Reduction Fund and opened up private investment in CCS.


Global CCS Institute: Global Status Report 2021 (globalccsinstitute.com)

## CCS: ECONOMICS

- The capital cost of CCS often involves investments in the order of hundreds of millions of dollars, sometimes exceeding US$1 billion[84].
- Therefore, CCS represents a significant financial investment; appropriate climate policies and regulations that place a penalty on carbon emissions are required to recover these costs and further CCS deployment.
- The same is true for retrofitting CCS into existing power plants, which requires space and extensive integration to accommodate the $CO_2$ capture plant.
- The most common way to operationalise the cost of CCS is $/t of $CO_2$ avoided.
- Power generation equipped with CCS, which can be around US$60/t$CO_2$ when in the vicinity to quality geologic storage resources is frequently used as a singular cost reference for CCS[84].
- The IPCC found that it would be 138% more expensive to reach global climate goals without the deployment of CCS[85].

## CCS: CAPTURING COST

**New-built power plants with CCS range from US$70 to $160/t $CO_2$ and can increase generation costs by 21% to 208%.**

- Natural gas processing has the lowest avg. avoidance cost of $CO_2$ because this industry already has the process of capturing $CO_2$ as part of its design[86].
- The cement sector has the highest carbon-capture because the capture of $CO_2$ is not inherent in the design of these facilities.
- High purity industrial $CO_2$ sources (such as coal-to-liquid and gas-to- liquids) have lower $CO_2$ capture costs starting from US$20/t $CO_2$.

$CO_2$ capture represents the greatest contribution to the cost of CCS, with the majority of the cost increases being due to change in the capture system.

## CCS: CAPTURE COST REDUCTION

- Experience demonstrates that the cost of CCS will fall.
- A study by the Global CCS Institute show that the cost of capture reduced from over US$100/t$CO_2$ at the Boundary Dam facility to below US$65/t$CO_2$ for the Petra Nova facility, just three years later[84].
- Most recent studies show capture costs (also using mature amine- based capture systems) for facilities that plan to commence operation in 2024-28, cluster around US$43/t$CO_2$.
- New technologies at pilot-plant scale promise capture costs around US$33/t$CO_2$.
- Pinned map of $CO_2$ capture facilities globally:

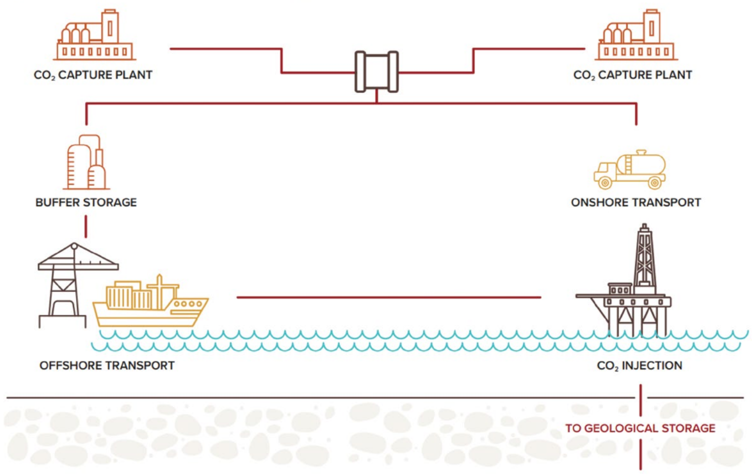
## CCS: TRANSPORT BY TRUCK, RAIL &MARINE

Safely and reliably transporting $CO_2$ from where it is captured to a storage site is an important stage in the CCS process and significant investment in transportation infrastructure is required to enable large- scale deployment.

Truck, rail and marine transport: $CO_2$ must be compressed and liquefied before transportation[87].

- Transport of $CO_2$ by truck and rail is possible for small quantities, however, given the large quantities of $CO_2$ that would be captured via CCS in the long-term, it is unlikely that truck and rail transport will be significant.
- Ship transportation can be an alternative option for many regions of the world. Shipment of $CO_2$ already takes place on a small scale in Europe and there is already a great deal of expertise in transporting liquefied petroleum gas, which has developed into a worldwide industry over a period of 70 years.
- Note: the liquefaction infrastructure is expensive under these forms of transport.

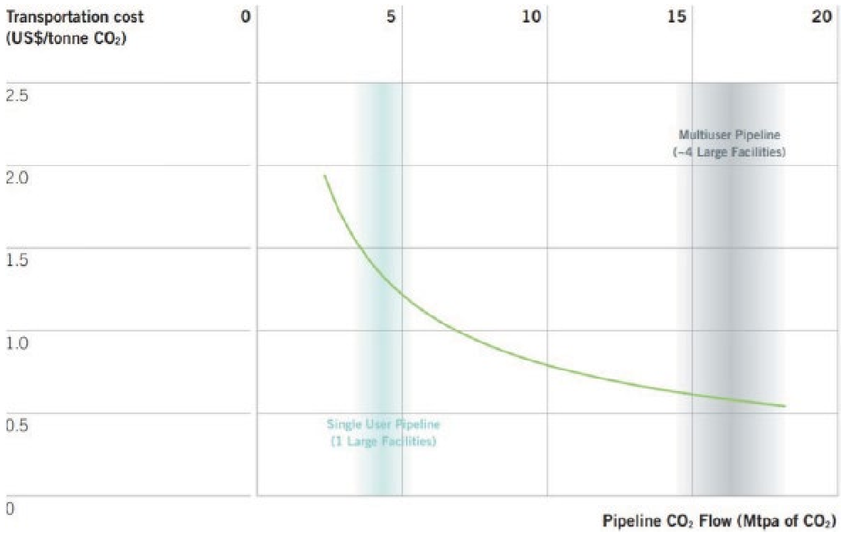
Figure 1: Transport overview of CCS technologies




Transport overview of CCS technologies (globalccsinstitute.com)

## CCS: TRANSPORT BY PIPELINE

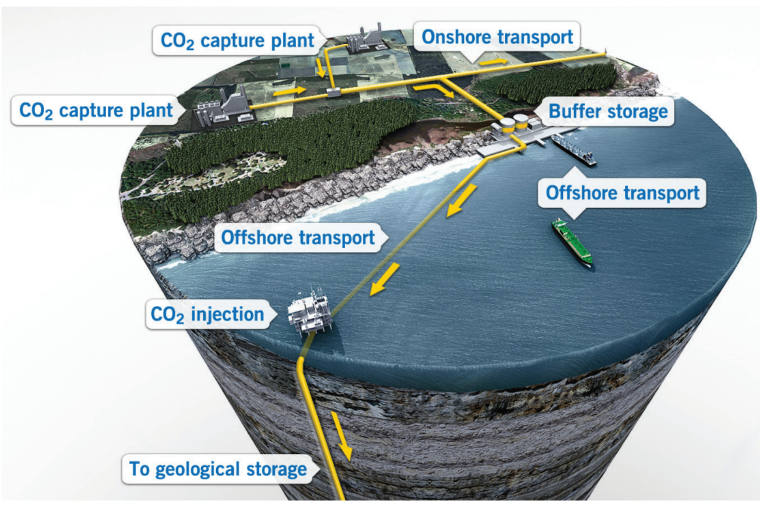
- Pipelines are - and are likely to continue to be - the most common method of transporting large quantities of $CO_2$ involved in CCS.
    - Extensive networks of pipelines already exist around the world, both on land and under the sea. However, the estimated $CO_2$ transportation infrastructure to be built in the coming 30-40 years is roughly 100 times larger than currently exists[87].
    - As the CCS industry matures more work will be required to understand optimal economic pipeline network design.




Transportation cost saving from increasing pipeline flow for 100km pipeline (globalccsinstitute.com)

## CCS: TRANSPORT COST

- Transport cost will be dependent on how much $CO_2$ is being transported and how far.
- Anything more than 2MtCOiyr is expected to prove pipeline as the cheapest method of transport




CCS transport options (globalccsinstitute.com)

## CCS: STORAGE

Onshore storage: the contribution of storage cost to the levelised cost of electricity (LCOE) was found to range from US$6-13/t$CO_2$ depending on whether the reservoir was 'good' or 'poorer'[84].

Offshore storage: dramatically increases the cost of $CO_2$ storage, especially in the existing relatively tight market for offshore drilling rigs and platforms.

- Water issues are also becoming apparent, not just for CCS projects but for other new hydrocarbon projects such as shale gas and coal seam methane. Thus, it is reasonable to expect that there may be more upfront (and on-going) work needed to ensure regulators are satisfied that there is little or no impact of CCS operations on water resources. This extra monitoring will increase costs.

Once $CO_2$ has been injected in the subsurface, monitoring of a $CO_2$ storage site occurs over its entire lifecycle from pre-injection to operations to post-injection. This enables the progress of $CO_2$ injection to be measured and provides assurance that storage is developing as expected.

Monitoring, measurement and verification (MMV) play a vital role in ensuring $CO_2$ storage meets operational, regulatory and community expectations. $CO_2$ storage uses MMV technologies and the experience of the oil, gas, and groundwater industries.

**Over 260 million tonnes of anthropogenic $CO_2$ has been injected and permanently stored to date-most** through enhanced oil recovery (EOR)[88]. Increasing oil production this way is a standard, mature and routine global operation. It is important to emphasise that $CO_2$ - EOR is not suitable for every oil field.

$CO_2$ storage costs are site specific and the local geology will drive the costs of $CO_2$ storage. Injection enhancements such as deviated wells and fracturing operations may increase the injection rates, but the trade-off will need to be evaluated in the specific site context.

## CCS: HUBS AND CLUSTERS

- There are incentives for **CCS projects to develop hubs and clusters**, as it will significantly reduce the unit cost of $CO_2$ storage through economies of scale, and offer commercial synergies that reduce the risk of investment. The costs per project are lower than can be achieved with stand-alone projects, where each $CO_2$ point source has its own independent and smaller scale transportation or storage requirement[89].
    - **A $CO_2$ cluster** may refer 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.
    - **A $CO_2$ hub** collects $CO_2$ from various emitters and redistributes it to single or multiple storage locations. For example, the South West Hub project in Western Australia seeks to collect $CO_2$ from various sources in the Kwinana and Collie industrial areas for storage in the Lesueur formation in the Southern Perth Basin.
    - **A $CO_2$ network** is an expandable collection and transportation infrastructure providing access for multiple emitters.
- Petrobras' Santos Basin CCS network was the first "CCS hub and cluster" in operation. It has a unique set up with 10 floating production storage and offloadings anchored in the Santos Basin off the coast of Rio de Janeiro, Brazil. The captured $CO_2$ is directly injected into the Lula, Sapinhoa and Lapa oil fields for enhanced oil recovery (EOR).

- The CCS project pipeline is growing more robustly than ever. From 75 million tonnes a year (Mtpa) at the end of 2020, the capacity of projects in development grew to 111 Mtpa in 2021 – a 48% increase[90].
- There are globally 135 commercial CCS facilities of varying capture capacity as at September 2021, 27 of which are operational and the remainder under construction or development.
- The United States leads the global league table hosting 27% of the pipeline, with other major contenders being the United Kingdom (6%), the Netherlands (4%) and Belgium (3%).

## LARGE SCALE CCS FACILITIES IN OPERATION

**Source:** Global CCS Institute

| Title | Country | Facility Status | Operation Date | Facility Industry | Capture Capacity Mtpa $CO_2$ | | Facility Storage Code |
|---|---|---|---|---|---|---|---|
| | | | | | Min | Max | |
| Terrell Natural Gas Processing Plant (formerly Val Verde Natural Gas Plants) | United States | Operational | 1972 | Natural Gas Processing | 0.4 | 0.5 | Enhanced Oil Recovery |
| Enid Fertilizer | United States | Operational | 1982 | Fertiliser Production | 0.1 | 0.2 | Enhanced Oil Recovery |
| Shute Creek Gas Processing Plant | United States | Operational | 1986 | Natural Gas Processing | 7 | 7 | Enhanced Oil Recovery |
| MOL Szank field $CO_2$ EOR | Hungary | Operational | 1992 | Natural Gas Processing | 0.059 | 0.157 | Enhanced Oil Recovery |
| Sleipner $CO_2$ Storage | Norway | Operational | 1996 | Natural Gas Processing | 1 | 1 | Dedicated Geological Storage |
| Great Plains Synfuels Plant and Weyburn-Midale | United States | Operational | 2000 | Synthetic Natural Gas | 1 | 3 | Enhanced Oil Recovery |
| Core Energy $CO_2$-EOR | United States | Operational | 2003 | Natural Gas Processing | 0.35 | 0.35 | Enhanced Oil Recovery |
| Sinopec Zhongyuan Carbon Capture Utilization and Storage | China | Operational | 2006 | Chemical Production | 0.12 | 0.12 | Enhanced Oil Recovery |
| Snøhvit $CO_2$ Storage | Norway | Operational | 2008 | Natural Gas Processing | 0.7 | 0.7 | Dedicated Geological Storage |
| Arkalon $CO_2$ Compression Facility | United States | Operational | 2009 | Ethanol Production | 0.23 | 0.29 | Enhanced Oil Recovery |
| Century Plant | United States | Operational | 2010 | Natural Gas Processing | 5 | 5 | Enhanced Oil Recovery |
| Petrobras Santos Basin Pre-Salt Oil Field CCS | Brazil | Operational | 2011 | Natural Gas Processing | 4.6 | 4.6 | Enhanced Oil Recovery |
| Bonanza BioEnergy CCUS EOR | United States | Operational | 2012 | Ethanol Production | 0.1 | 0.1 | Enhanced Oil Recovery |
| Coffeyville Gasification Plant | United States | Operational | 2013 | Fertiliser Production | 0.9 | 0.9 | Enhanced Oil Recovery |
| Air Products Steam Methane Reformer | United States | Operational | 2013 | Hydrogen Production | 1 | 1 | Enhanced Oil Recovery |
| Lost Cabin Gas Plant | United States | Operation Suspended | 2013 | Natural Gas Processing | 0.7 | 0.7 | Enhanced Oil Recovery |

**Source:** Global CCS Institute

| Title | Country | Facility Status | Operation Date | Facility Industry | Capture Capacity Mtpa $CO_2$ | | Facility Storage Code |
|---|---|---|---|---|---|---|---|
| | | | | | Min | Max | |
| PCS Nitrogen | United States | Operational | 2013 | Fertiliser Production | 0.2 | 0.3 | Enhanced Oil Recovery |
| Boundary Dam 3 Carbon Capture and Storage Facility | Canada | Operational | 2014 | Power Generation | 0.8 | 1 | Various Options Considered |
| Quest | Canada | Operational | 2015 | Hydrogen Production | 1.2 | 1.2 | Dedicated Geological Storage |
| Uthmaniyah $CO_2$-EOR Demonstration | Saudi Arabia | Operational | 2015 | Natural Gas Processing | 0.8 | 0.8 | Enhanced Oil Recovery |
| Karamay Dunhua Oil Technology CCUS EOR Project | China | Operational | 2015 | Methanol Production | 0.1 | 0.1 | Enhanced Oil Recovery |
| Abu Dhabi CCS (Phase 1 being Emirates Steel industries) | United Arab | Operational | 2016 | Iron And Steel Production | 0.8 | 0.8 | Enhanced Oil Recovery |
| Illinois Industrial Carbon Capture and Storage | United States | Operational | 2017 | Ethanol Production | 0.55 | 1 | Dedicated Geological Storage |
| Petra Nova Carbon Capture | United States | Operation Suspended | 2017 | Power Generation | 1.4 | 1.4 | Enhanced Oil Recovery |
| CNPC Jilin Oil Field $CO_2$ EOR | China | Operational | 2018 | Natural Gas Processing | 0.35 | 0.6 | Enhanced Oil Recovery |
| Gorgon Carbon Dioxide Injection | Australia | Operational | 2019 | Natural Gas Processing | 3.4 | 4 | Dedicated Geological Storage |
| Qatar LNG CCS | Qatar | Operational | 2019 | Natural Gas Processing | 2.2 | 2.2 | Dedicated Geological Storage |
| Alberta Carbon Trunk Line (ACTL) with North West Redwater Partnership's Sturgeon Refinery $CO_2$ Stream | Canada | Operational | 2020 | Hydrogen Production | 1.3 | 1.6 | Enhanced Oil Recovery |
| Alberta Carbon Trunk Line (ACTL) with Nutrien $CO_2$Stream | Canada | Operational | 2020 | Fertiliser Production | 0.2 | 0.3 | Enhanced Oil Recovery |

Commercial CCS facilities in operation - 2021 (globalccsinstitute.com)

## BLUE HYDROGEN MAKES UP A LARGE PORTION OF THE CCS DEVELOPMENT PIPELINE

Blue hydrogen is natural gas-based hydrogen produced via stream methane reforming repaired with carbon capture. It is a promising sub segment of the CCS market. Hydrogen as an energy carrier can be used to displace higher carbon-intensity fuels in transportation, steel production, power and a variety of chemical applications. Blue hydrogen is an option to facilitate this fuel switching.

There are currently seven commercial facilities producing blue hydrogen in operation. Their total combined production capacity is 1.3 to 1.5 Mtpa, depending on assumed availability. In addition, there are a further 18 blue hydrogen facilities in development as at June 2021[90].

National hydrogen roadmaps and emissions reduction targets are the drivers of the recent interest in blue hydrogen.

| Facility | $H_2$ Production Capacity (tonnes per day) | $H_2$ Production Process | $H_2$ Use | Operational Commencement |
|---|---|---|---|---|
| **Enid Fertiliser** | 200 (in syngas) | Methane reformation | Fertiliser production | 1982 |
| **Great Plains Synfuel** | 1300 (in syngas) | Coal gasification | Synthetic natural gas production | 2000 |
| **Air Products** | 500 | Methane reformation | Petroleum refining | 2013 |
| **Coffeyville** | 200 | Petroleum coke gasification | Fertiliser production | 2013 |
| **Quest** | 900 | Methane reformation | Bitumen upgrading (synthetic oil production) | 2015 |
| **ACTL Sturgeon** | 240 | Asphaltene residue gasification | Bitumen upgrading (synthetic oil production) | 2020 |
| **ACTL Nutrien** | 800 | Methane reformation | Fertiliser production | 2020 |

Commercial Blue Hydrogen CCS facilities – 2021 (globalccsinstitute.com)

## BLUE HYDROGEN

| Technology |
| --- |
| • The three main technologies used to produce low-carbon hydrogen are:<br>- **Gas reforming (mostly from steam methane reforming) with CCS**;<br>- **Coal gasification with CCS; and**<br>- **Electrolysis powered by renewables.**<br>• The advantages of low-carbon hydrogen production through gas reforming and coal gasification with CCS, centre around the maturity of the technologies, scale and commercial viability. |

| Maturity |
| --- |
| • Low-carbon hydrogen has been produced through gas reforming and coal gasification with CCS, for almost two decades.<br>• For example, the Great Plains Synfuel Plant in North Dakota, US, commenced operation in 2000 and produces approximately 1,300 tonnes of hydrogen (in the form of hydrogen rich syngas) per day, from brown coal. |

| Scale |
| --- |
| • For hydrogen to make a meaningful contribution to global greenhouse gas emission reductions, it will need to be produced in very large quantities to displace a significant proportion of current fossil fuel demand.<br>• Scaling up low-carbon hydrogen production **with CCS is a large contender to scaling up with the use of electrolysis.** |

| Commercial Viability |
| --- |
| • Low-carbon hydrogen produced using gas reforming and gasification technologies with CCS is proven, operating at commercial scale and available for deployment right now. When produced on a large scale, low-carbon hydrogen made with **CCS can be a lower cost option than electrolysis**.<br>• The Global CCS Institute estimate that from the assumed amount of 530Mt of hydrogen that will be in demand by 2050, the cost of the essential infrastructure required to support **green** hydrogen could cost 20-30x more than the infrastructure required for **blue** hydrogen[90]. |

## CARBON CAPTURE UTILISATION AND STORAGE (CCUS)

- There are other options for carbon than geological sequestration. CCUS and CCS only differ in that CCUS does not include geological injection of $CO_2$. Capture methods are almost identical for CCUS and CCS. CCUS is promising alternative path to decarbonise inputs of a variety of products and to provide an alternative revenue stream for carbon capture.
- $CO_2$ injection into concrete is the most common market for CCUS carbon. $CO_2$ is introduced when concrete is mixed. Once it hardens, the $CO_2$ is trapped indefinitely. It is claimed that this improves the compressive strength of concrete. However, concrete vendors pay a premium for this type of product.

## CCS: BENEFITS & CHALLENGES

| Benefits |
| --- |
| • CCS can significantly decarbonise oil and gas, fossil fuel-based power generation and a variety of industrial processes without a fundamental disruption of the business models or products. Existing infrastructure can be utilised, that would otherwise be decommissioned, to help defer shut-down cost.<br>• CCS reduces total system costs of electricity supply by providing reliable, dispatchable generation capacity when fitted on flexible fossil fuel power plants.<br>• Provides hard-to-decarbonise sectors like cement, steel and smelting a commercialised solution to decarbonise.<br>• When paired with biomass, which captures atmospheric $CO_2$ naturally, with geological storage can lead to net negative carbon emission.<br>• CCS enables low-carbon hydrogen to displace a variety of carbon intensive fuels. |

| Challenges |
| --- |
| • Cost of CCS will make coal-fired electricity more expensive than renewable energy.<br>• CCS technology would not generate a viable return in the absence of a carbon price. The $CO_2$ tax must be higher than the $CO_2$ avoidance cost to justify the higher risk, capital and lower efficiency of utilising CCS.<br>• Reported CCS costs are challenging to compare as few similarities exists across projects. This leads to challenges in forecasting capex cost reduction.<br>• Unknown consequences of storing gas underground, such as leakage from underground or undersea reservoirs.<br>• Scarcity of potential sites and capacity compared to volumes of greenhouse gas needed to be sequestered on an ongoing basis.<br>• Existing power stations unlikely to be able to have carbon capture technology retrofitted.<br>• CCS currently requires more coal than conventional plants to cover the energy needs of CCS (although R&D is rapidly improving efficiencies), and that extra coal must first be mined (which has environmental effects) and transported to the plant (which takes energy).<br>• Infrastructure required would take years to build. |

## CCS: OUTLOOK

**Near-term outlook for CCS is mixed; some sub segments will rise as others falter:**

### BEAR MARKET

- Power plants will no longer be attractive for CCS deployment
- Pairing CCS with cement and steel manufacturing is costly, and so far, potential applications have only been theoretical/pilot stage
- As the market will not meaningfully scale, capex will not significantly fall
- Carbon prices of approximately US$90/metric ton are necessary to make most applications economical and that is unlikely in the near term in most geographies

### BULL MARKET

- Blue hydrogen will come to represent an even greater portion of the CCS pipeline
- Favourable economics and a supportive regulatory and political environment help the US maintain its leader status in the CCS market
- China will become the No.2 ranked market, as they have a large new built coal-fired plant fleet that will need decarbonisation
- Pilot will be designed to figure out how to pair CCS in the industrial sector, but most likely nothing at scale will emerge in the near term

# CHAPTER 2:
# LEGAL & REGULATORY FRAMEWORK

## ENSURING SAFE AND ENVIRONMENTALLY SOUND CCS

- The environmental integrity of CCS is an overriding concern for policy makers. This is partly a matter of ensuring that the $CO_2$ captured and stored remains isolated from the atmosphere in the long term; and partly about ensuring that the capture, transport and storage elements do not present other risks to human health or ecosystems.
- Therefore, law and regulation remains a critical element of a government's policy response to support the development and deployment of CCS. Robust legal and regulatory frameworks provide certainty for businesses eager to engage in innovation, and the deployment of CCS.
- Although the components of CCS are all known and deployed at commercial scale, integrated systems are new. A clear regulatory framework is thus required, and the EU's CCS Directive provides this.

## CCS UNDER 2030 POLICY FRAMEWORK FOR CLIMATE AND ENERGY

Background:

- The European Commission's proposal for a 2030 climate and energy policy framework acknowledges the role of CCS in reaching the EU's long-term emissions reduction goal.
- Significant emissions cuts are needed in the EU's energy and carbon- intensive industries. As theoretical limits of efficiency are being reached and process-related emissions are unavoidable in some sectors, CCS may be the only option available to reduce direct emissions from industrial processes on the scale needed in the longer term.
- In the power sector, CCS could be a key technology for fossil fuel- based generation. It could help balance an electricity system with increasing shares of variable renewable energy.
- To ensure that CCS can be deployed in the 2030 timeframe, increased R&D efforts and commercial demonstration are essential over the next decade. A supportive EU framework will be necessary through continued and strengthened use of auctioning revenues.

## EU'S LEGAL FRAMEWORK FOR CCS

- Amendments have been made to the **European Union Emissions Trading Scheme (EU ETS) Directive** to include $CO_2$ capture, transport by pipelines and the geological storage of CO2 within its scope of activities.
- The directive on the geological storage of $CO_2$ **("CCS Directive")** establishes a legal framework for the environmentally safe geological storage of $CO_2$. It covers all $CO_2$ storage in geological formations in the EU and the entire lifetime of storage sites.
- The CCS Directive also contains provisions on the capture and transport components of CCS, though these activities are covered mainly by existing EU environmental legislation, such as the **Environmental Impact Assessment (EIA) Directive or the Industrial Emissions Directive**, in conjunction with amendments introduced by the CCS Directive.

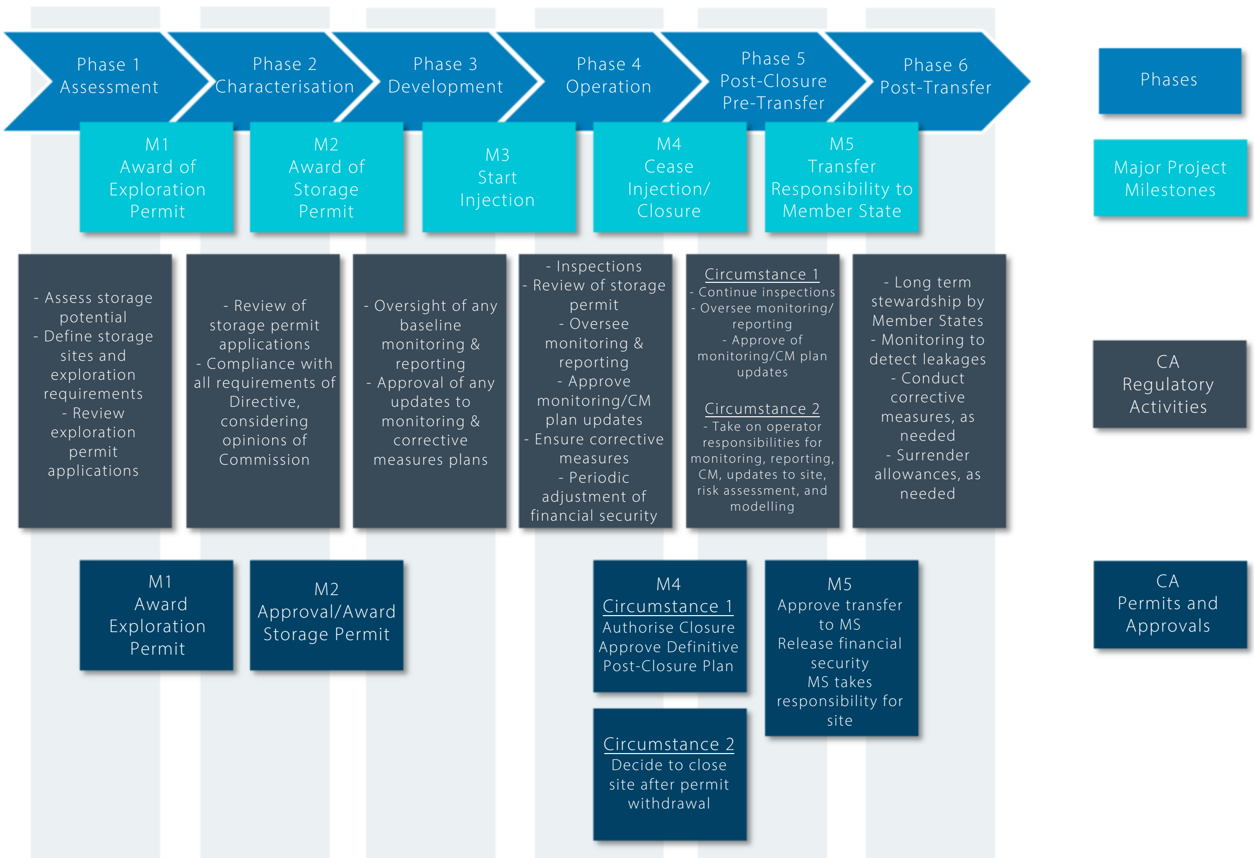
## THE EU EMISSIONS TRADING SYSTEM (EU ETS)

- The EU ETS is the cornerstone of the EU's drive to reduce $CO_2$ emissions
- The system works by putting a limit on overall emissions. Within this limit, companies can buy and sell emission allowances as needed. This '**cap-and-trade**' approach gives companies the flexibility they need to cut their emissions in the most cost-effective way[91].
- By putting a price on carbon and thereby giving a financial value to each tonne of emissions saved, the EU ETS has placed climate change on the agenda of company boards across Europe. Pricing carbon also promotes investment in clean, low-carbon technologies.
- Companies are allowed to buy credits from **emission-saving projects** around the world, in particular in least developed countries, the EU ETS acts as a driver of investment in clean technologies and low-carbon solutions (e.g. CCS) globally.
- Around 45% of total EU greenhouse gas emissions are regulated by the EU ETS[91].
- One of the barriers in the current legislation is the fact that only those projects where the $CO_2$ is transported by pipelines can benefit from the EU ETS carbon price. Facilities that plan to transport $CO_2$ for storage by other means than pipelines, for example by ship or truck, would still need to pay for captured $CO_2$ emissions. A good example here is the **Norwegian full-scale project** which will transport $CO_2$ by ship.

## CCS DIRECTIVE: A FRAMEWORK FOR THE ENTIRE LIFE CYCLE OF GEOLOGICAL STORAGE OF $CO_2$ ACTIVITIES

- The CCS Directive lays down extensive requirements for the **selecting sites** for $CO_2$ storage. A site can only be selected if a prior analysis shows that, under the proposed conditions of use, there is no significant risk of leakage or damage to human health or the environment[92].
- No geological storage of $CO_2$ will be possible without **a storage permit**.
- The substances captured to be stored must consist overwhelmingly of $CO_2$ to prevent any adverse effects on the security of the transport network or the storage site. The operation of the **site must be closely monitored** and corrective measures taken in the case that leakage does occur.
- The Directive also covers **closure and post-closure obligations**, and sets out criteria for the **transfer of responsibility** from the operator to the Member State.
- Finally, the operator **must establish a financial security before the injection of $CO_2$** starts to ensure that the requirements of the CCS Directive and the Emissions Trading Directive can be met.
- Operators are included in the Emissions Trading System, which ensures that in case of leakage they have to surrender emission allowances for any resulting emissions. Liability for local damage to the environment is dealt with by using the Directive on Environmental Liability. Liability for damage to health and property is left for regulation at Member State level.
- Furthermore, barriers to CCS in existing waste and water legislation are removed, and the Large Combustion Plants Directive is amended to require an assessment of capture readiness for large plants.

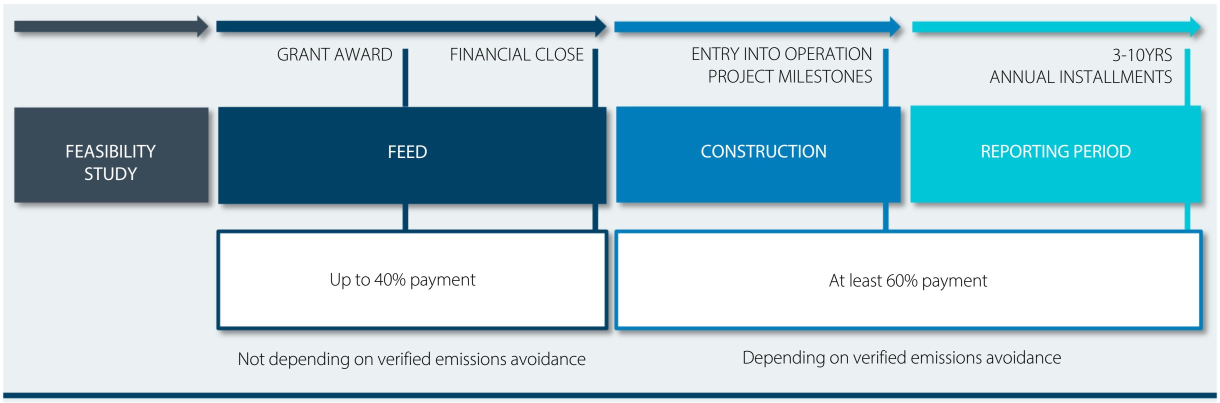
## SUMMARY OF $CO_2$ STORAGE LIFE CYCLE PHASES AND MILESTONES




$CO_2$ life cycle phases (researchgate.net)

## INNOVATION FUND

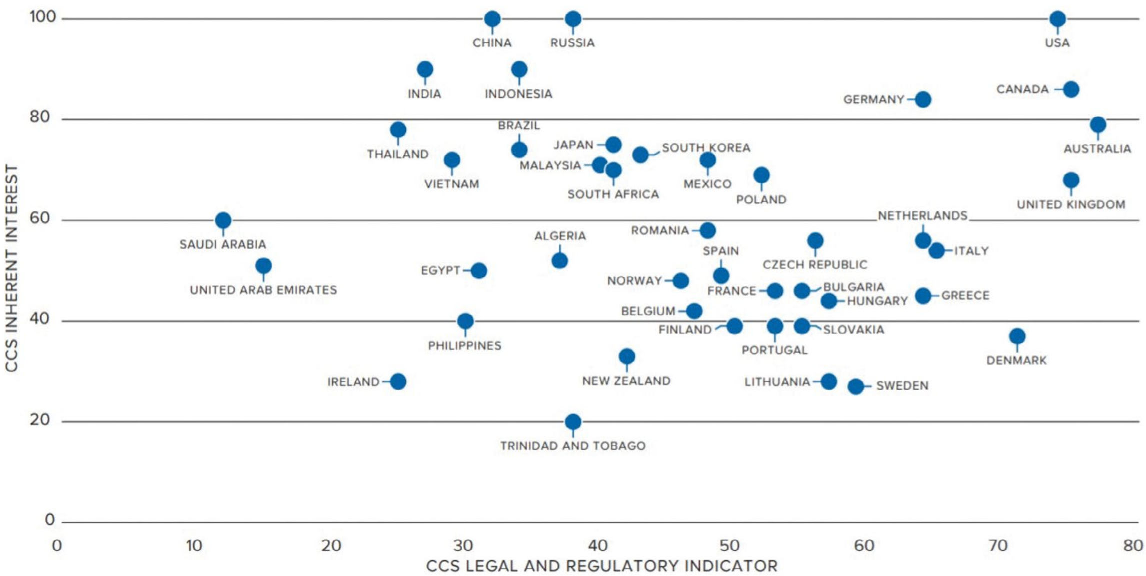
- The Innovation Fund is the **largest fund available for financing CCS** in Europe. It finances innovative low-carbon technologies and processes in energy intensive industries, CCUS, renewable energy and energy storage projects.
- Up to 40% of grant payments will be given in the project preparation phase, based on predefined milestones. The remaining 60%, linked to innovation, are based on verified emissions avoidance outcomes and can continue for up to 10 years[88].
- The first call for proposals was made in 2020, followed by regular calls until 2030.
- Around **ten billion euros** are to be made available, based on a carbon price (which is currently around €20). 450 million EU ETS allowances will be sold on the carbon market in the period 2020-30.




Disbursements based on milestones (globalccsinstitute.com)

## CCS LEGAL AND REGULATORY INDICATOR (CCS-LRI)

- Australia was included in Band A of the CCS-LRI and received the highest score of all the countries reviewed in the 2018 assessment.
- Australia has a sophisticated and largely consistent approach to CCS at both the Commonwealth and state levels. Its comprehensive legal and regulatory framework addresses all stages of the CCS project lifecycle.
- However, there are a number of remaining gaps and obstacles within the Australian regime that have yet to be addressed. For example, the treatment of long-term liability and indemnification, which some states have treated differently in their legislative models[93].



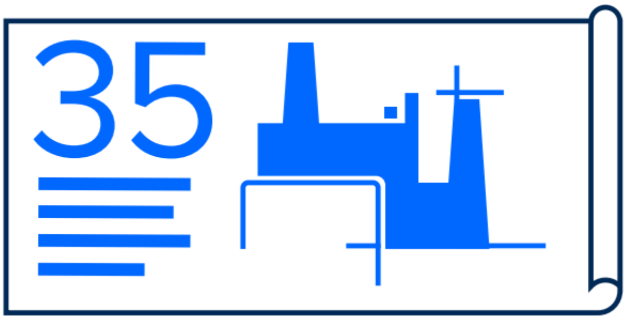

CCS chart – legal and regulatory indicator (globalccsinstitute.com)

CCS IN EUROPE

**CCS Facilities in Europe**

The EU made climate neutrality by 2050 a **legally binding target,** along with reducing 2030 net GHG emissions at least **55 per cent compared to 1990 levels.**


There are now **35 projects** in development across Europe.




The UK outlined its intention to establish four CCUS industrial clusters by 2030, capturing 10 Mtpa of $CO_2$.


European CCS (globalccsinstitute.com)

# APPENDIX 1: CCS CASE STUDIES

## CASE STUDY: GORGON $CO_2$ INJECTION

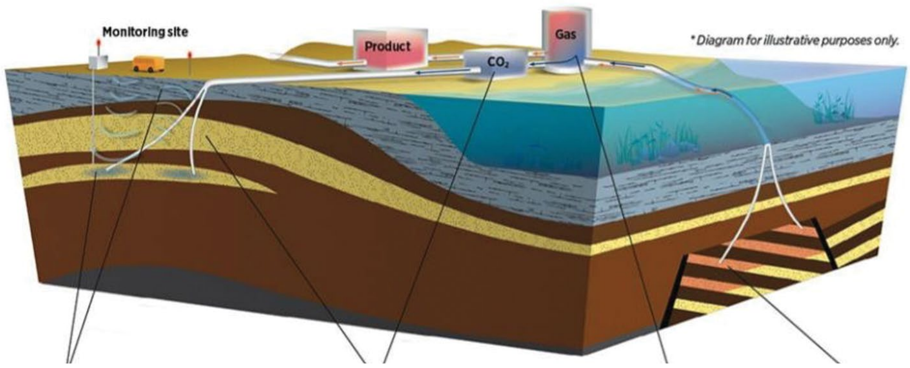
| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Gorgon Carbon Dioxide Injection | Operational | Australia | 2019 | Natural Gas Processing | 4.00 capture capacity mtpa $CO_2$ | Industrial Separation | Dedicated Geological Storage |

**Project Overview:**

- The Gorgon carbon dioxide injection project is an important part of the Gorgon Gas Development Project, which is developing the Greater Gorgon Area gas fields off the northwest coast of Western Australia.
- The project involves the design, construction and operation of facilities to inject and store $CO_2$ into a deep reservoir unit, known as the Dupuy Formation, more than two km beneath Barrow Island.
- The gas in the Gorgon field contains 14% naturally occurring $CO_2$ therefore, it is important that this is separated prior to gas processing and liquefaction.
- Injection of $CO_2$ started in early August 2019.

**Project Highlights:**

- The project will reduce greenhouse gas emissions from the Gorgon Project by approx. 40%.
- With a predicted project lifespan of more than 40 years, it is expected that 100 million tonnes of $CO_2$ will be injected into the Dupuy Formation over the life of the Gorgon Project.
- Nine injection wells at three drill centres which are connected to the LNG plant via a seven km underground pipeline




CCS: The 2020 state of the market (globalccsinstitute.com)

PROJECT PARTNERS

- Chevron
- Osaka Gas
- ExxonMobil
- Tokyo Gas
- Shell
- Jera

## CASE STUDY: SLEIPNER $CO_2$ STORAGE

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Sleipner $CO_2$ Storage** | Operational | Norway | 1996 | Natural Gas Processing | 1.00 capture capacity mtpa $CO_2$ | Industrial Separation | Dedicated Geological Storage |

**Project Overview:**

- Completed in 1996, Sleipner was the world's first commercial storage project at a deep saline reservoir.
- After the enactment of a carbon tax in Norway, Equinor began developing this CCS project at its existing Sleipner natural-gas processing facility.
- $CO_2$ is injected into a deep saline reservoir located 2,600 to 3,300 feet below seafloor.

**Project Highlights:**

- Without CCS, the facility would have been subject to a taxes of nearly 1 million kroner per day.
- Approximately 15.5m tones of $CO_2$ have been injected since operation began; no evidence of leakage has been detached.
- Equinor and its partners will disclose datasets from the Sleipner field; in a push to advance innovation and development on the field of $CO_2$ storage.

Sleipner gas field (equinor.com)

PROJECT PARTNER

Equinor

## CASE STUDY: SNOHVIT $CO_2$ STORAGE

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Snøhvit $CO_2$ Storage** | Operational | Norway | 2008 | Natural Gas Processing | 0.70 capture capacity mtpa $CO_2$ | Industrial Separation | Dedicated Geological Storage |

**Project Overview:**

- SnØhvit is a gas field that is located 140km offshore, northwest of the city of Hammerfest in Finnmark county, Norway.
- It is not operated by platform, but by subsea templates at a depth of between 250 and 350m.
- The gas is transported through a pipeline to shore for processing at the Melk0ya facility, and is then shipped out on liquefied natural gas (LNG) tankers.
- The gas contains about 5-8% $CO_2$, which is separated from the hydrocarbons as part of the processing and piped back to a formation at the edge of the Sn0hvit reservoir, where it is stored 2600m beneath the seabed permanently.
- $CO_2$ is injected into a sandstone formation called Tubaen. A shale cap which lies above the sandstone will seal the reservoir and ensure that the $CO_2$ stays underground without leaking to the surface.
- Operating since 2008, storing about 0.7Mtpa in a depleted natural gas field, under the sea bed.

**Project Highlights:**

- At full capacity on SnØhvit, 700,000 tonnes of $CO_2$ will be stored per year, which equals the emission volume from 280,000 cars.

SnØhvit gas field (offshore-technology.com)

### PROJECT PARTNERS

- Total
- Statoil
- GDF Suez
- Hydro
- Hess
- Petoro

## CASE STUDY: PORTHOS, NEVERLAND

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Port of Rotterdam CCUS Backbone Initiative (porthos) | Advanced development | Netherlands | 2023 | Various | 2.00-5.00 capture capacity mtpa $CO_2$ | Various | Dedicated Geological Storage |

**Project Overview:**

- Porthos is preparing a project to transport $CO_2$ from industry in the Port of Rotterdam and store this in empty gas fields beneath the North Sea.
- The $CO_2$ that will be transported and stored by Porthos, will be captured by various companies. The companies will supply their $CO_2$ to a collective pipeline that runs through the Rotterdam port area. The $CO_2$ will then be pressurised in a compressor station.
- The $CO_2$ will be transported through an offshore pipeline to a platform in the North Sea, approx. 20 km off the coast. From this platform, the $CO_2$ will be pumped in an empty gas field. The empty gas fields are situated in a sealed reservoir of porous sandstone, more than 3 km beneath the North Sea.

**Project Highlights:**

- It is expected that, in its early years, the project will be able to store approximately 2.5 million tonnes of $CO_2$ per year.
- Porthos has been granted Project of Common Interest (PCI) status by the European Commission, this means that permit applications are more streamlined and the applications are made simultaneously as one total package of permits.
- The $CO_2$ infrastructure in Rotterdam can be seen as the first step in developing a CCUS hub in the Rotterdam region, which offers future possibilities for other regions to transport and store $CO_2$ to depleted gas fields beneath the North Sea.

Porthos industrial area (portofrotterdam.com)

### PROJECT PARTNERS

- Port of Rotterdam
- Gasunie
- EBN

## CASE STUDY: NORTHERN LIGHTS CCS

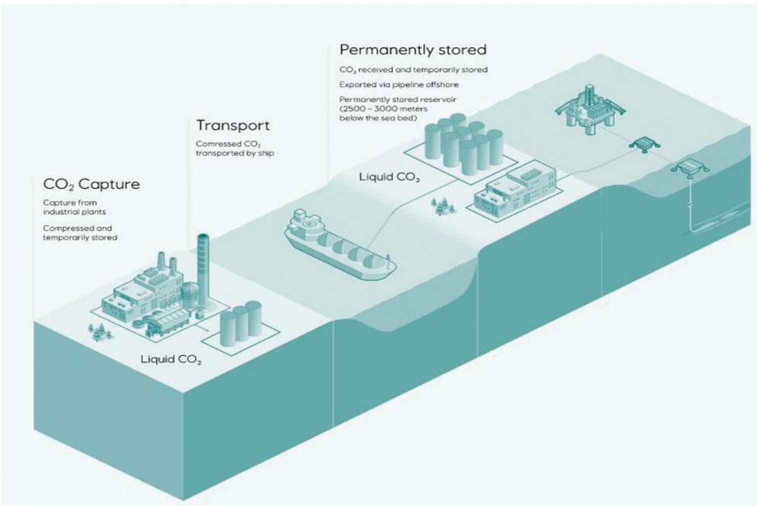
| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Norway Full Chain CCS | Advanced development | Norway | 2023-2024 | Cement production and waste-to-energy | 0.80 capture capacity mtpa $CO_2$ | Various | Dedicated Geological Storage |

**Project Overview:**

- The full-scale Northern Lights project is a result of the Norwegian government's ambition to develop a full-scale CCS value chain in Norway by 2024. As part of this ambition the government issued feasibility studies on capture, transport and storage solutions in 2016. Combined, these studies showed the feasibility of realising a full-scale CCS project.
- The project involves capturing $CO_2$ at multiple industrial facilities region (cement and waste-to-energy), then transporting it for storage. The facility will uniquely use ship-based transport, thus enabling the storage of $CO_2$ for major sources across North West Europe. The transport and storage element of the project – Northern Lights - will be open access infrastructure.

**Project Highlights:**

- Phase 1 includes capacity to transport, inject and store up to 1.5 million tonnes of $CO_2$ per year. Once the $CO_2$ is captured onshore, it will be transported by ships, injected and permanently stored some 2,500 metres below the seabed in the North Sea.
- Exploitation licence EL00l "Aurora" was awarded in January 2019.
- In March 2020 the Eos confirmation well was drilled. The well will be used for injection and storage of $CO_2$.
- The use of sea-based transport means industry across Western Europe can also store and transport their $CO_2$ through Northern Lights.




Northern lights CCS process (equinor.com)

### PROJECT PARTNERS

- Equinor
- Shell
- Total

## CASE STUDY: HYNET NORTH WEST

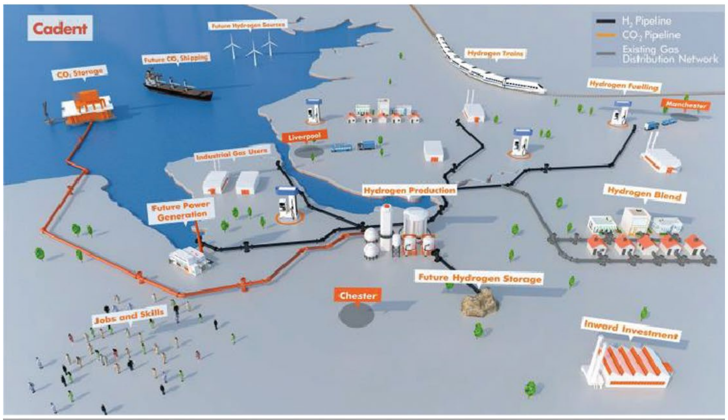
| | | | | | | | |
|---|---|---|---|---|---|---|---|
| HyNet North West | Early Development | United Kingdom | Mid 2020s | Hydrogen Production | 1.50 capture capacity mtpa $CO_2$ | Industrial Separation | Dedicated Geological Storage |

**Project Overview:**

- HyNet North West is a hydrogen energy and Carbon Capture, Usage and Storage (CCUS) project. The goal of HyNet is to reduce carbon emissions from industry, homes and transport and support economic growth in the North West of England.
- HyNet is based on the production of hydrogen from natural gas. It includes the development of a new hydrogen pipeline; and the creation of the UK's first CCUS infrastructure.

**Project Highlights:**

- HyNet saves over one million tonnes of carbon dioxide emissions every year. The equivalent of taking more than 600,000 cars off the road
- Phase 1 (2018 - 2023): includes technical assessment, due diligence and construction on CCUS infrastructure.
- Phase 2 (2023- 2026): includes operational launch of CCUS, with 1 million tonnes $CO_2$ captured per year, and the operational launch of hydrogen supply.
- Phase 3 (2027-2035): will extend the hydrogen delivery infrastructure to new geographies, complete development to the hydrogen transport fueling infrastructure, and increase CCUS capacity to 25 million tonnes per year.
- The"2050 vision" includes deploying the HyNet Northwest model across the UK and increasing CCS capacity to 100 million tonnes per year.




Hynet north west project structure (hydrogen-central.com)

### PROJECT PARTNERS

- Cadent
- University of Chester
- Pilkington
- Progressive Energy
- Unilever
- ENI

# GREEN STEEL

INSIDE



Research Paper


Author:
**John Hirjee**

# EXECUTIVE SUMMARY

The primary purpose of this paper is to educate and examine whether and when green steel could become commercially viable and implications for metallurgical (also known as 'met' or coking) coal.

The world produces and consumes about 1.8 billion tonnes of steel per year[94], about 71% of which is from traditional coal fired blast furnaces[95]. Average $CO_2$ emissions are about 2 tonnes of $CO_2$ per tonne of steel produced. Steelmaking using coal accounts for circa 8% of global greenhouse gas emissions.

Hydrogen ($H_2$) based steelmaking is potentially an alternative to traditional coal fired blast furnace/basic oxygen furnace (BOF). The main ways to reduce carbon intensity of steel are:

1) Reduce use of metallurgical coal by replacing it with green hydrogen; and

2) the use of renewable energy to power steel making operations.

ArcelorMittal estimates a cost of up to EUR40 billion for it to move to hydrogen based steelmaking[96] (against its current market cap of ~EUR28.5 billion), excluding $H_2$ production & distribution infrastructure. Who bears the cost? Will it be governments/taxpayers or consumers of steel manufacturing? Ultimately, the buck will stop with the consumer. Carbon free steel is likely to cost more.

The scale of this change is very significant. According to Bank of America Research, studies in Sweden and Germany suggest that moving the entire steel industry to $H_2$ based steelmaking requires a capacity increase in electricity generation of 10-15%. Ultimately large parts of the economy would need to be rebuilt, from electricity generation and storage to transmission, hydrogen electrolysers and steel plants.

Greater Europe produces around 200Mtpa steel. Of this, 60% (120Mtpa) is via blast furnace. So to replace this product with hydrogen based steelmaking would require = 3.5MWh/t x 120Mtpa = 420M MWh = 420TWh. Compare this to European power generation last year at ~3,000TWh (=14%).

- Most importantly, hydrogen could significantly increase demand for renewable power generation. In addition, for steel to be considered green, all power sources must be considered green as well.
- Green hydrogen-based steel production is likely to become one key technology that shapes the route to decreasing emissions. Europe is examining the potential for green steel. However, the thin margins in the steel industry make the decision to adopt green steel a difficult economic choice.
- Overall, the cost-competitiveness of green hydrogen is still some years away, although global interest is significantly increasing. This could lead to a break-through in cost efficiencies. We estimate that green hydrogen could become commercial this decade.
- Given the capital and infrastructure required to make commercial green steel, we are of the view that the electricity generation infrastructure required could mean that green steel will take at least a decade or more to commercialise. Indeed, the technology required to be adopted to make green steel could take decades to develop as pilot plants are only currently being planned. Of course, this is predicated on the emergence of commercial-scale green hydrogen.
- Therefore, metallurgical coal is likely to remain an important product for the Australian economy in the medium term.
- Future availability of cheap energy from renewables and green hydrogen will be the two key drivers for the adoption of hydrogen-based steel. Australia's abundant, but intermittent, wind and solar resources are better suited to making hydrogen-intensive commodities such as green steel.
- Green steel is not yet commercially viable. It is heavily reliant on access to very cheap renewable electricity which in turn is used to produce cheap green hydrogen. Europe is leading the way with a number of green steel pilot projects planned. High carbon prices are a key catalyst behind this.
- Overall, the economic viability of green hydrogen is still some years away, although global interest in hydrogen is significantly increasing. The emergence of commercial green hydrogen is likely to occur this decade.
- Given the capital and infrastructure required to make commercial green steel, we are of the view, the electricity generation infrastructure required could mean that green steel will take at least a decade or more to commercialise.
- Therefore, metallurgical coal is likely to remain an important product for the Australian economy in the medium term.
- Electric Arc Furnace (EAF) using renewable power seems to be the future of the industry for the short to medium term, despite implications of scrap steel supply. EAF steelmaking has a lower carbon intensity to BOF steelmaking.

# WHAT IS GREEN STEEL?

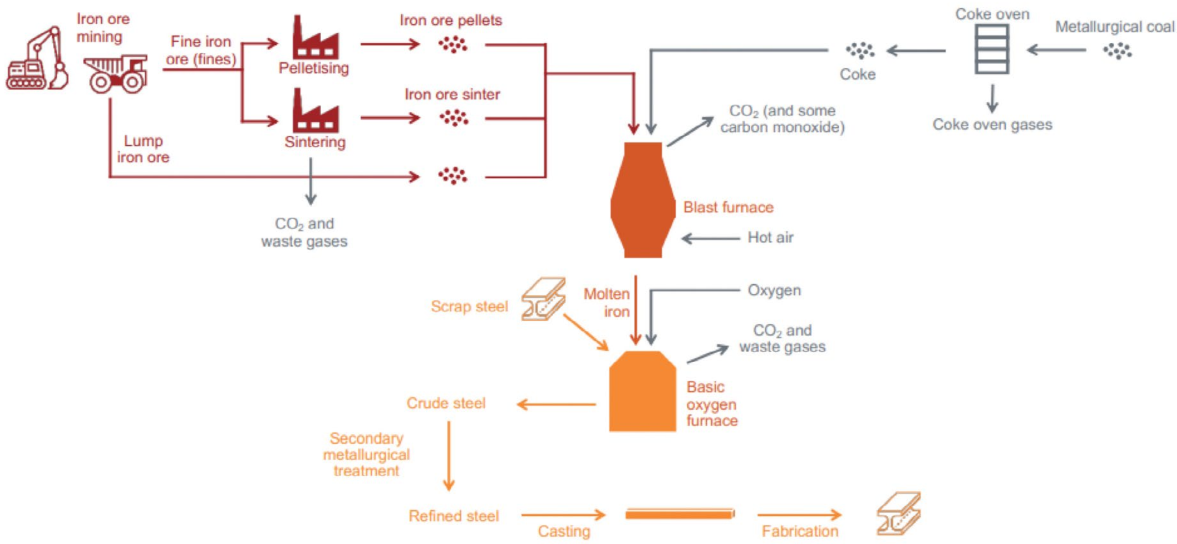
- Steel is one of the core pillars of today's society and, as one of the most important engineering and construction materials, it is present in many aspects of our lives. However, the industry now needs to cope with pressure to reduce its carbon footprint from both environmental and economic perspectives.
- Green Steel is produced when metallurgical coal is replaced with green hydrogen in the steel making process and/or when renewable power is used in the energy intensive process of making steel through the EAF route.
- Green hydrogen is produced from water using renewable-powered electrolysis. The future of green steel is inextricably linked with commercial green hydrogen. The commercial threshold of green hydrogen needs to be met to further the progress of commercially available green steel.
- Green steel pilot plants, largely in Europe, have been the initial industry response to determine its commercial viability. European countries are often viewed as the best placed to produce green steel due to the prevalence of a carbon price and availability of renewable energy.
- There are two different approaches to hydrogen based steelmaking[98]:

    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 steel making.
    2. Incremental: ThyssenKrupp is implementing hydrogen injection in existing blast furnaces. This could deliver up to 20% reduction in $CO_2$ emissions from the steelmaking process if implemented across all the company's facilities. The capital cost should be much lower with positive impact on $CO_2$ emissions, sooner, as long as the hydrogen is green.

# STEEL MAKING TECHNOLOGY

- Primary steelmaking has two methods: BOF (Basic Oxygen Furnace or Blast Furnace) and the EAF (Electric Arc Furnace).
- The BOS method principally uses iron ore, metallurgical coal and scrap steel to produce steel. At high temperatures, oxygen is blown through the metal, which reduces the carbon content to between 0-1.5%. 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[99]. During the process, the metallurgical coal is injected into the bottom of the furnace shaft where it is used as an additional reducing agent.

**Figure A.1: Integrated steel-making**

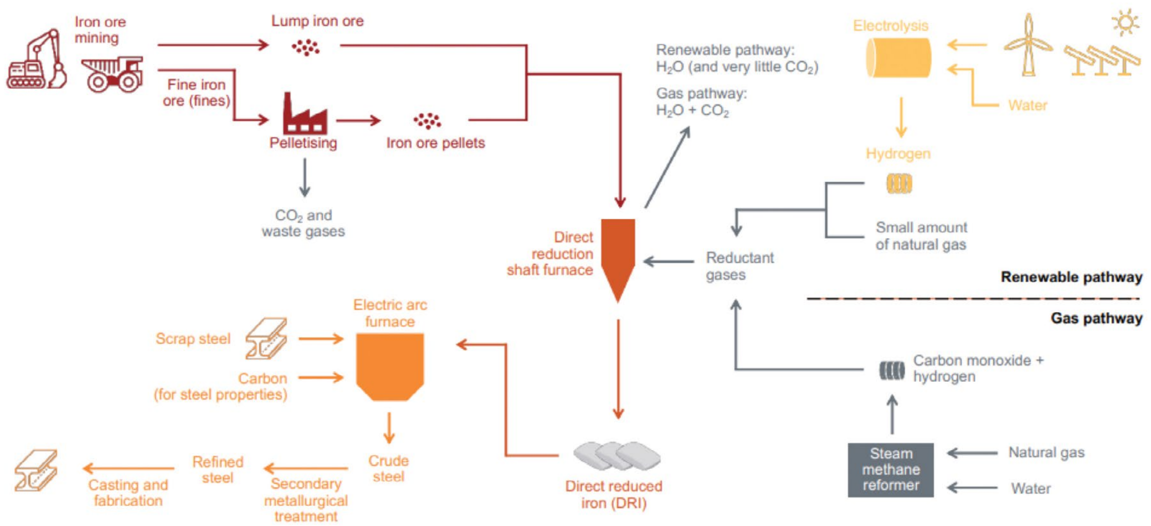



*Note: Scrap steel is added to the basic oxygen furnace to control the temperature.*
*Source: Grattan analysis. Some icons sourced from flaticon.com (2020).*

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

- The EAF method feeds recycled steel scrap through a high-power electric charge (with temperatures of up to 1,650 degrees Celsius) to melt the metal and convert it into steel. The EAF route uses primarily recycled steels and direct reduced iron (DRI) or hot metal and electricity. 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[99].
- It is relatively easy to make low-emissions recycled steel from scrap. No reductant is required, and so the main source of emissions is the electricity used to melt the steel (in an 'electric arc furnace'). Even using coal-based electricity, recycled steel produces about one quarter of the emissions of new 'ore-based' steel made using coal.
- However, good quality scrap steel is not widely available in the quantities required to make EAF steel-making a prime source of steel.
- Global steel production comprises 71% via BOS and 29% via EAF steel making[99].
- DRI (direct reduced iron), used in the EAF steel making process, is made using natural gas instead of coal, in a process known as 'direct reduction'. This involves splitting natural gas into a mix of carbon monoxide and hydrogen, and using these gases to reduce iron ore to iron metal. Gas-based direct reduction roughly halves the carbon dioxide emitted per tonne of steel thus making the EAF route more environmentally friendly than BOF[98].
- But lower-emissions steel is still not 'green steel'. For this there needs to be a carbon-free reductant. Other very low emissions steel-making techniques are possible, such as gas-based direct reduction with carbon capture and storage.

**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 renewable hydrogen or natural gas (grattan.edu.au)

# GREEN STEEL EXPORT PATHWAYS

- Green steel export pathways are inclusive of[100]:

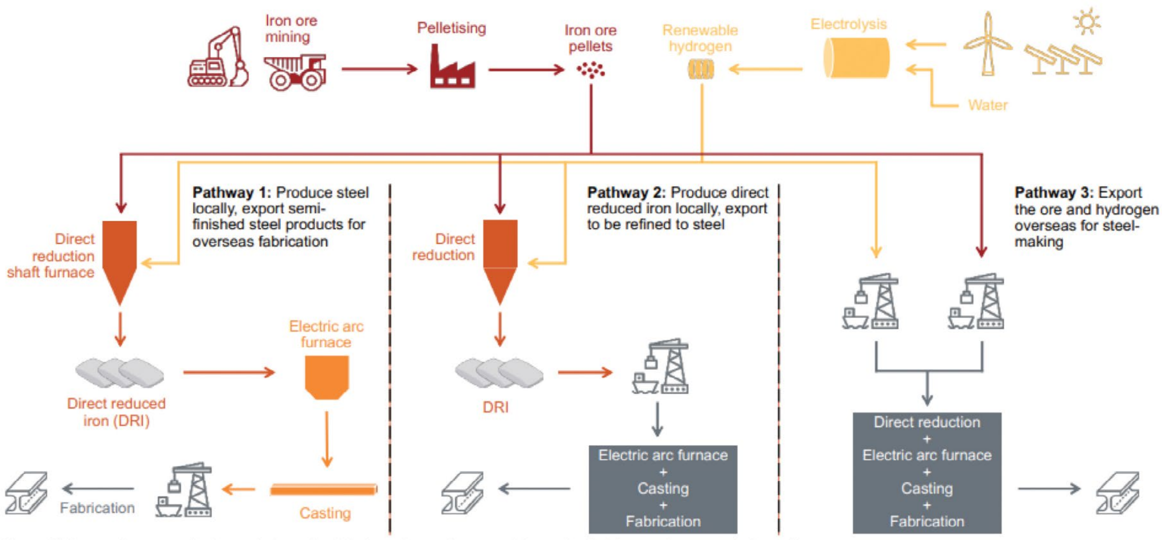
    1) Pathway 1 - Produce steel locally, export semi-finished steel products for overseas fabrication.

    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.

**Figure 2.3: Green steel export pathways**



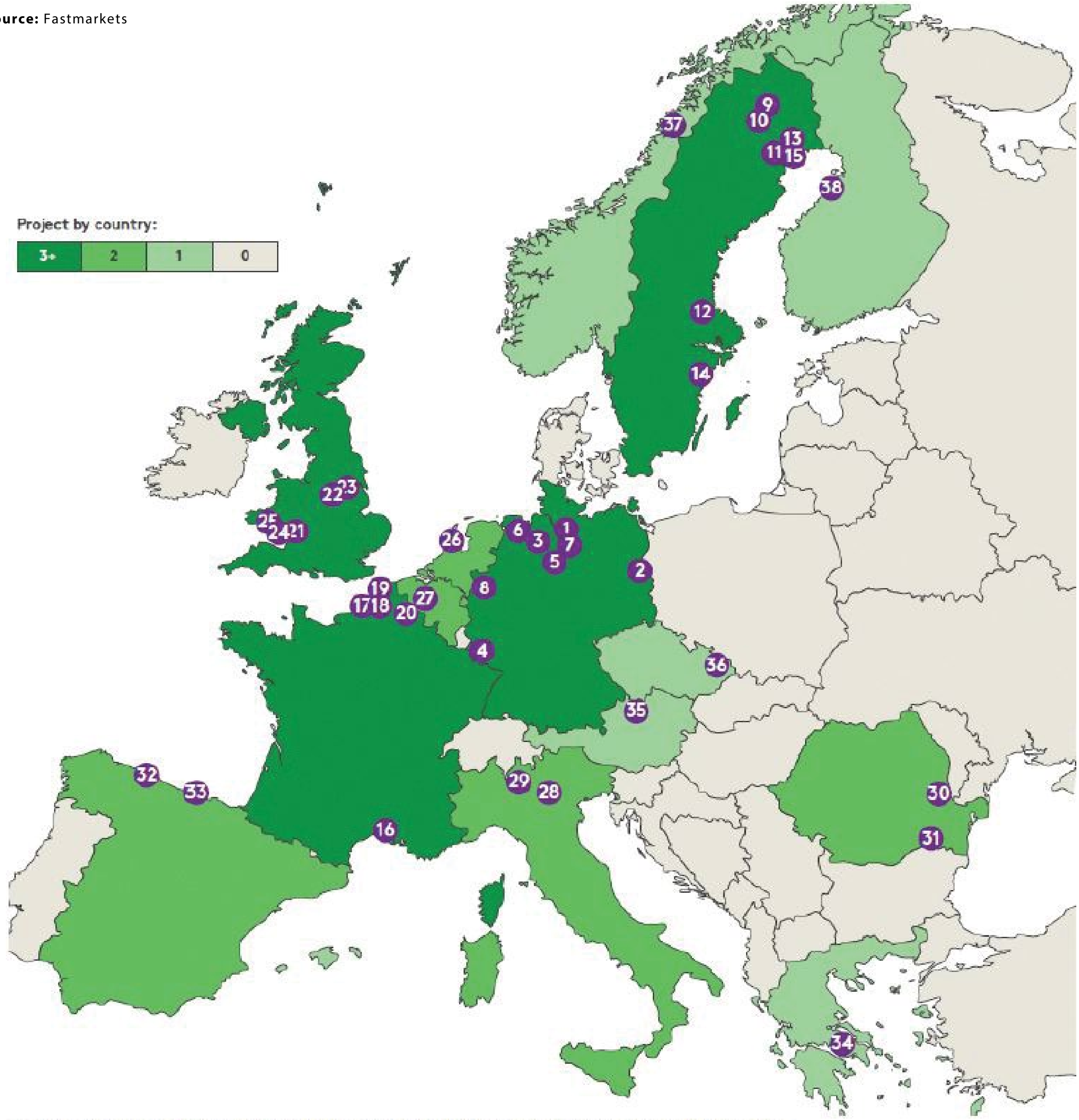

*Notes: All three pathways require low-emissions electricity in each step. Iron ore mining and pelletising need not occur in Australia.*
*Source: Grattan analysis. Some icons sourced from flaticon.com (2020).*

Export pathways (grattan.edu.au)

# GREEN STEEL PILOT PLANTS

- Europe is leading the way with a number of green steel pilot plants to determine its commercial viability.
- This is driven by the European Parliament's 'Green Steel for Europe' Pilot Project. This initiative supports the EU in achieving the 2030 climate and energy targets and the 2050 long-term strategy for a climate neutral Europe by proposing effective solutions for low or carbon neutral steelmaking.

**Source:** Fastmarkets




Decarbonisation projects announced by steelmakers across the region (amm.com/pdf/2021/Fastmarkets_Green_Steel_European_Map_2021.pdf)

**Source:** Fastmarkets

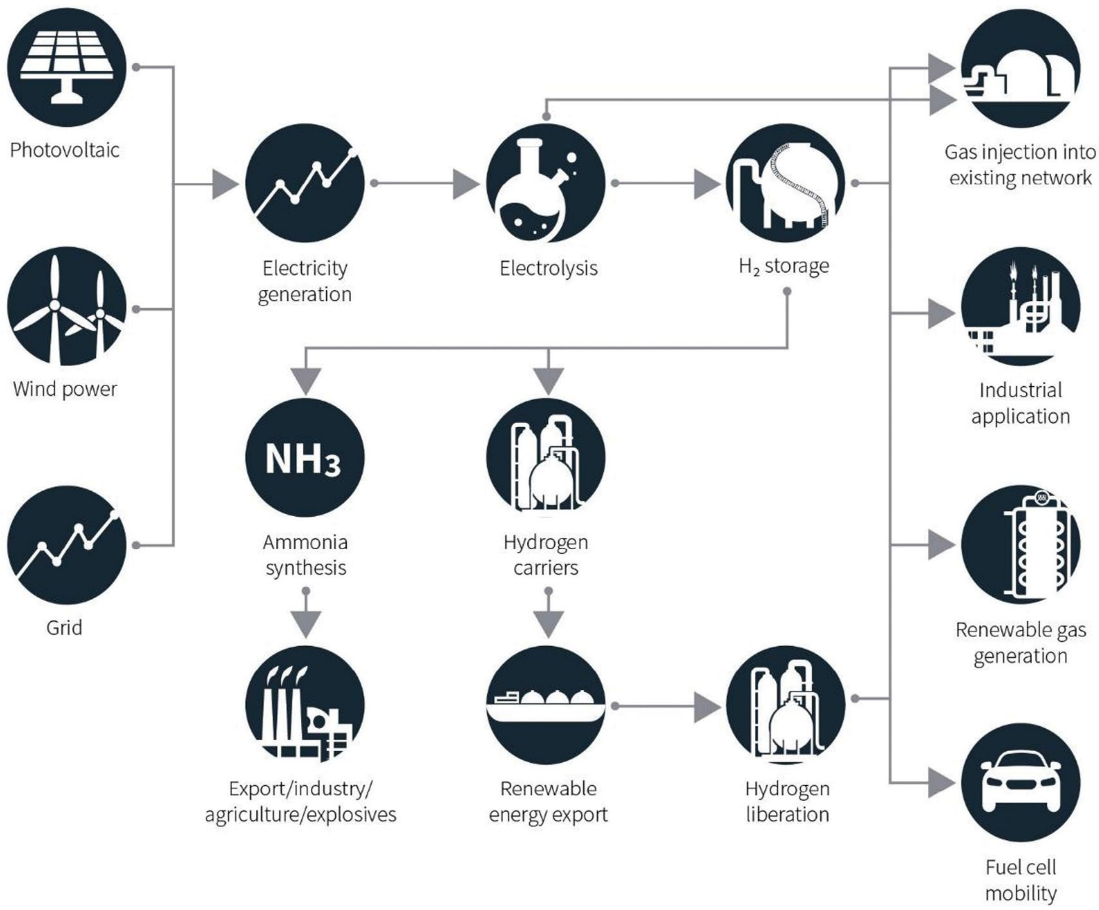
| | | |
|---|---|---|
| **Germany** | | |
| 1 | ArcelorMittal, Hamburg | DRI-EAF, H2Hamburg will use hydrogen as the reductant in DRI production initially with 'grey' hydrogen (non-renewable hydrogen sourced from natural gas) |
| 2 | ArcelorMittal, Eisenhüttenstadt | Pilot DRI plant and EAF |
| 3 | ArcelorMittal, Bremen | • Electrolyser for hydrogen production use<br>• Industrial DRI plant and EAF |
| 4 | Rogesa, joint subsidiary of Dillinger & Saarstahl, Dillingen | • To use hydrogen-rich coke gas in BOFs as a reducing agent and process gases<br>• New circular cooler dedusting system at sinter plant |
| 5 | Salzgitter (Salcos) Wind$H_2$, Salzgitter | Wind Hydrogen Salzgitter - construction of seven wind turbines to power electrolyser for hydrogen production |
| 6 | Salzgitter (Salcos), Wilhelmshaven | DRI plant with upstream electrolysis plant for hydrogen |
| 7 | Salzgitter (Salcos), Peine | To produce green strip steel via scrap in EAF |
| 8 | Thyssenkrupp, Duisburg | • To use hydrogen as a reducing agent for iron ore in BOF<br>• 1.2 million tpy DRI plant in Duisburg with integrated BOF melting unit<br>• Feasibility study for water electrolysis plant as part of green hydrogen goals<br>• Thyssenkrupp and TSR recycling to explore use of scrap in BOF<br>• Will replace four BOFs with DRI plants and green hydrogen |
| **Sweden** | | |
| 9 | Hybrit (SSAB, LKAB and Vattenfall), LKAB Malmberget | Plant to manufacture fossil-free iron-ore pellets |
| 10 | Hybrit (SSAB, LKAB and Vattenfall), Gällivare | Production plant to produce fossil-free DRI |
| 11 | Hybrit, (SSAB, LKAB and Vattenfall) Luleå | • Will build 100 cubic metre underground hydrogen facility<br>• DRI-pilot plant to replace coking coal with hydrogen and fossil-fuel free electricity |
| 12 | Ovako, Hofors | • To use hydrogen to heat steel before rolling<br>• Will build hydrogen plant |
| 13 | H2GreenSteel, Boden-Luleå | Hydrogen steel plant |
| 14 | SSAB, Oxelösund | Convert BOFs to EAFs |
| 15 | SAB, Luleå | Convert BOFs to EAFs |
| **France** | | |
| 16 | ArcelorMittal, Fos-sur-Mer | Study to build second Carbalyst plant for BOF waste gas |
| 17 | Dillinger, Dunkirk | To modernise pusher furnace No2 to achieve a 2.7% reduction in $CO_2$ emissions |
| 18 | ArcelorMittal, Dunkirk | • Carbon capture pilot project and IGAR, Hybrid BOF using DRI gas injection<br>• DRI plant and arc furnace. Working with Air Liquide for hydrogen |
| 19 | Liberty Steel, SHS & Paul Wurth, Dunkirk | MOU to explore 1 GW hydrogen electrolysis plant and 2 million tpy DRI plant |
| 20 | Stahl-Holding-Saar (SHS)/ Saarstahl, Ascoval (previously Liberty France) | Green rail produced via EAF |

**Source:** Fastmarkets

| | | |
|---|---|---|
| **UK** | | |
| 21 | Liberty Steel, Newport | Plans for new EAF and sustainable power |
| 22 | Liberty Steel, Rotherham | To produce rebar from domestic scrap in EAF via green steel strategy |
| 23 | British Steel, Scunthorpe | To increase the use of scrap in its steelmaking process to reduce its carbon emissions |
| 24 | Celsa UK, Cardiff | 56% of electricity is from renewable sources |
| 25 | Tata Steel, Neath Port Talbot | Exploring carbon capture as part of South Wales Industrial Cluster (SWIC) |
| **Netherlands** | | |
| 26 | Tata Steel, IJmuiden | • Seeking permits for carbon capture and storage under the North Sea; water electrolysis facility to produce hydrogen and oxygen<br>• HIsarna technology |
| **Belgium** | | |
| 27 | ArcelorMittal, Ghent | • Carbalyst /Steelanol - to capture waste gases from BOF and biologically convert these into bio-ethanol<br>• Torero to convert waste wood into bio-coal to displace fossil fuel coal currently injected into the BOF |
| **Italy** | | |
| 28 | Duferco, Brescia | Beam furnace using hydrogen fuel-injected burners. Power via green PPA |
| 29 | Tenaris, Edison and Snam | Hydrogen-based steelmaking via electrolyser |
| **Romania** | | |
| 30 | Liberty Steel, Galati | To build DRI plant & 2 EAFs as part of green steel strategy, to use domestic scrap |
| 31 | Beltrame | 600,000 tpy green rebar and wire rod mill |
| **Spain** | | |
| 32 | ArcelorMittal, Asturias, Gijón | • Coke oven gas project using grey hydrogen<br>• 2.3 million tpy green hydrogen DRI and 1.1 million tpy hybrid EAF |
| 33 | ArcelorMittal, Sestao | Full-scale zero carbon-emissions steel plant, via green hydrogen and renewable electricity. DRI via Gijón |
| **Greece** | | |
| 34 | Corinth Pipeworks, Thisvi | To be carbon-neutral via renewable electricity and other carbon-offsetting measures |
| **Austria** | | |
| 35 | voestalpine, Primetals Technologies, Linz | • Pilot plant to process iron ore concentrate from ore beneciation using hydrogen gas as reduction agent<br>• Convert three BOFs to EAFs |
| **Czech Republic** | | |
| 36 | Liberty, Ostrava | Replace four tandem furnaces with two hybrid furnaces |
| **Norway** | | |
| 37 | Celsa, Statkraft & Mo industripark AS, Mo i Rana | Hydrogen Hub Mo, a plant for electrolysis-based hydrogen production for use in the manufacture of reinforcing steel |
| **Finland** | | |
| 38 | SSAB, Raahe | Convert BOFs to EAFs |

# THE CASE FOR GREEN HYDROGEN

- Hydrogen is a versatile energy carrier with an energy density more than twice that of natural gas. Today's technology for producing hydrogen is predominantly based on fossil fuels.
- Hydrogen is unique among liquid and gaseous fuels in that it emits no $CO_2$ emissions when burned. In addition, it is a high efficiency, low polluting fuel that can be used for transportation, heating, and power generation to decarbonise industry or as a $CO_2$ neutral feedstock for chemical processes (such as ammonia fertilisers).
- Around 71% is 'grey' hydrogen (steam methane reformation, or SMR) while most of the rest is 'brown' hydrogen gasification of coal or lignite)[23]. These processes have been around for decades. The challenge is dealing with the carbon and high emissions that result. The future for the current technology is all about 'green' and 'blue' hydrogen. Blue is where the production process is paired with carbon capture and storage (CCS), however this not yet widely commercial and needs scaling up too.
- With green hydrogen the technology is different, with the hydrogen produced from water by renewables-powered electrolysis. The process is zero carbon and produces very pure hydrogen, whereas grey or brown hydrogen contains impurities. Green hydrogen is also both a form of energy storage and can be used as a balancing tool for renewables.




Green hydrogen value chain (advisian.com)

# COMMERCIAL ASPECTS OF GREEN HYDROGEN

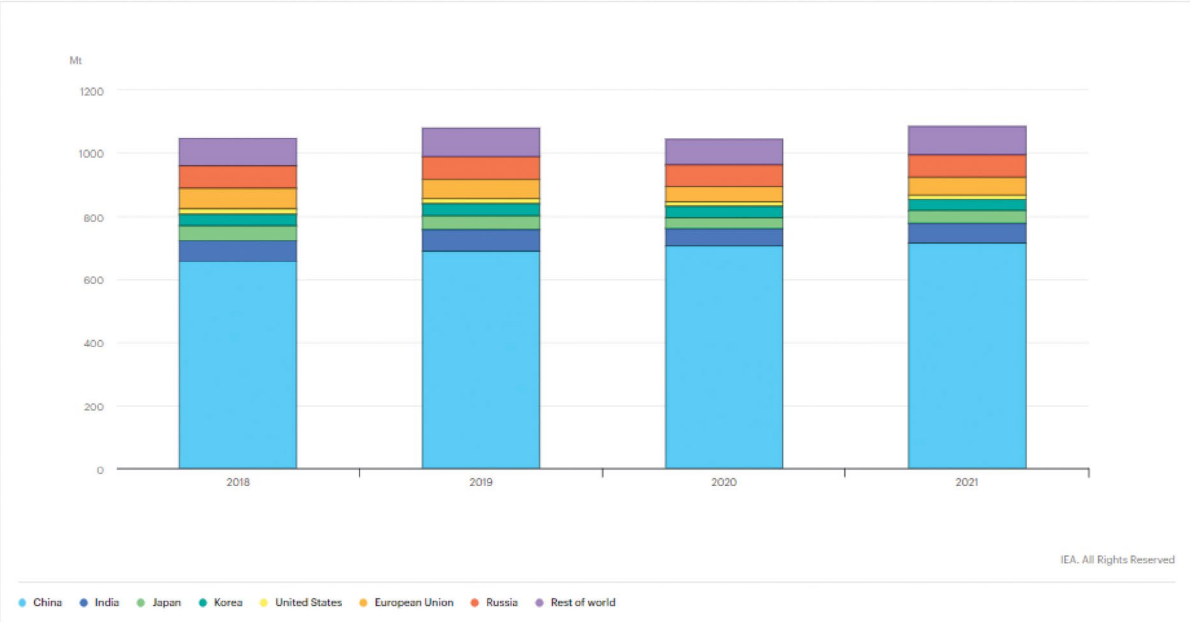
- The electrolysers that make hydrogen are flexible - they can turn on and off in response to the availability of renewable electricity. This, plus the ability to store hydrogen, means that hydrogen can be produced when energy is abundant and stored for when it is scarce. Hydrogen storage acts as a buffer between an intermittent renewable energy supply and the continuous steel-making process.
- Currently, fossil-fuel-based processes produce hydrogen at a lower cost than renewable electricity electrolysis technologies. Electrolysis technology is relatively immature, and ongoing volume driven innovation is expected to bring process costs down in the near to mid-term, becoming competitive with thermochemical production processes by 2025 according to the CSIRO[6]. The US Department of Energy has a 2020 cost target for hydrogen by electrolysis of US$2.00/kg[22] (about A$2.70/kg), in line with the estimates by the CSIRO for 2025.
- Ultimately hydrogen must be cost-competitive with other fuels in specific application areas if it is to achieve widespread adoption.
- Hydrogen production is still high cost and inefficient. Electrolysis is capital expensive, wastes a proportion of the electrical energy used and requires large amounts of water. Moreover, once produced hydrogen storage can be challenging due to its small molecular properties.
- It is estimated that a carbon price of US$40/tonne in 2030 is required to get hydrogen on a level with SMR-produced hydrogen paired with CCS[101].
- Realistically, it will largely take this current decade before blue and green hydrogen start to make a meaningful contribution to decarbonisation. They are expected to account for 10% of global energy demand by 2050[101].

# COMMERCIALISATION TIMETABLE FOR GREEN STEEL

- There are two pre-requisites for the commencement of commercial green steel - renewable electricity and commercial green 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 hydrogen and the requirement to reduce emissions, it would not be surprising for commercialisation of hydrogen to occur sooner rather than later.
- A price on carbon would be a significant driver towards green steel.
- 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 steel making process.
- Current information suggests it is likely commercial green steel would require significant augmentation of electricity networks to make green steel on a viable, commercial basis. Therefore, it is envisaged that green steel would take at least a decade or two to become viable.
- EAF steel making is the most likely process for a low emissions steel industry in the medium term, despite implications for scrap steel supply.

# METALLURGICAL COAL

- Metallurgical (coking) coal is a key raw material in steel production. It is used as both an energy source for a blast furnace and as a reducer of iron. As iron occurs only as iron oxide in the earth's crust, the ores must be converted, or 'reduced', using carbon. The primary source of this carbon is metallurgical coal. Coke, made by carburising met coal (i.e. heating in the absence of oxygen at high temperatures), is the primary reducing agent of iron ore[99].
- The abundance of coal, its low cost, and ease of processing make it a necessary commodity for the steel industry. It is expected that met coal will not be made redundant at least for the short to mid term.




Metallurgical coal demand (iea.org)

# METALLURGICAL COAL'S IMPORTANCE TO AUSTRALIA

Australia is the fourth largest producer of coal worldwide, producing around 476 million tonnes of coal in 2020, with around 40% of it being metallurgical coal[102].

The value of Australia's metallurgical coal exports have held at historic highs for several months. Export earnings are forecast to surge with recent price movements, rebounding from A$23 billion in 2020-21 to peak above A$50 billion in 2021-22[103]. It is the nation's 2nd largest export by value after iron ore accounting for 15% of total exports.

In 2019-20, Australia was the world's largest exporter of metallurgical coal[97], exporting ~177mt - almost all of its production. The Australian coal industry paid over A$7 billion in royalties and over A$200 million in payroll tax for state governments. The coal industry is estimated to have provided around 50,000 direct jobs in 2020 and a further 120,000 indirect jobs across Australia[104].

# STEEL

- Steel is used in the construction, machinery, automotive and other manufacturing sectors which represents around 52%, 16%, 12% and 12% respectively of global steel consumption[103].
- China is the world's largest producer of steel. China's share of global crude steel production in 2021 was ~53%. Chinese mills have been previously impacted by high domestic scrap prices.
- Lower global steel production in recent months reflects a moderation of economic (and industrial output) growth rates to lower, longer-run trend levels, as well as production cuts and weakened steel demand in China. New outbreaks of the pandemic and ongoing supply chain issues are downside risks to global growth and steel consumption over the outlook[103].
- However, world demand for steel is estimated to grow in 2022, reflecting the continued recovery in economic activity and industrial output underway in most major economies.

# SCRAP STEEL

- Scrap steel used in the EAF, displaces DRI and subsequently reduces the need for iron ore in the steelmaking process. But steel scrap is not widely available and this is reflected in the price of scrap steel.
- The National Development & Reform Commission (NDRC), China's economic planning body, published a plan for the country's resource recycling industry last year to accelerate the development of a low-carbon circular economy. The plan included a goal for scrap usage in the steel sector to reach 320 million tonnes in 2025. In 2020, scrap usage was around 260 million tonnes[105].
- Looking into the next decade, the share taken by EAF steel was estimated to reach 40% of global steel output, against 30% in 2020, with EAF steels in China at 25% of the country's total in 2030, compared with around 10% last year[105].
- High scrap prices due to the shortage of scrap does limit the profitability of EAF steelmakers and inhibit their expansion. The BOS steelmaking route will remain dominant for at least the next 20 years, supporting iron ore consumption.

# THE IMPORTANCE OF STEEL-MAKING IN AUSTRALIA

- The Australian steel industry produced 5.5m tonnes of steel in 2021, ranking 27th in world steel production by volume[106].
- The steel industry contributes ~A$30 billion to the Australian economy annually.
- Every A$1 million worth of output in the Australian steel industry generates approximately A$225,300 in tax revenue[106].
- Over 110,000 people are directly employed in the Australian steel industry. For every person employed directly by the steel industry, this creates as many as six full-time jobs in related and downstream industries.

# AUSTRALIA IS WELL PLACED TO MAKE GREEN STEEL

- Australia's combination of wind and solar resources is likely to give it an energy-cost advantage in a decarbonised world.
- Australia's lower-cost hydrogen, plus the high cost of hydrogen transport, give it a clear **advantage in undertaking direct reduction iron production** and exporting it - instead of refining direct iron into steel which gives low-wage countries an advantage in that step of the process.
- However, in order for Australian steel to be competitive, a price on carbon may need to be implemented. Even then, for the short to mid- term, green steel would come at a premium, compared to its carbon intensive alternatives.

# COVID-19 IMPACT ON GLOBAL STEEL DEMAND

Global steel demand has fared better with the pandemic than with the financial crisis. According to the World Steel Association, a healthy rebound is expected in 2022.

- The operational side has also performed well, however the pandemic will bring a far-reaching transformation of society, offering additional challenges to the steel industry. In particular, structural changes in the steel using sectors, and increased environmental pressure[107].
- Steel will be part of the solution and will also see new opportunities from new investments required for the low-carbon society.

# CONCLUSION

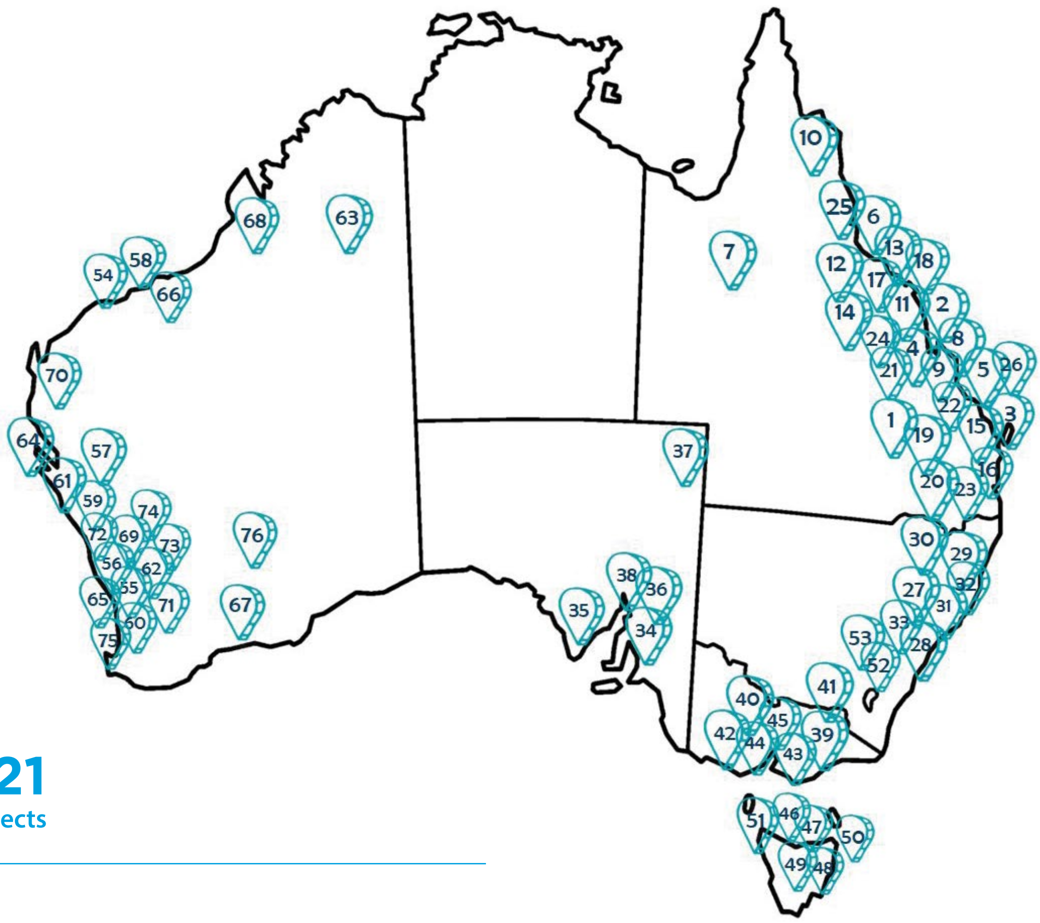
- Future availability of cheap energy from renewables and green hydrogen will be the two key drivers for the adoption of hydrogen-based steel. Australia's abundant, but intermittent, wind and solar resources are better suited to making hydrogen-intensive commodities such as green steel.
- Green steel is not yet commercially viable. It is heavily reliant on access to very cheap renewable electricity which in turn is used to produce cheap green hydrogen. Europe is leading the way with a number of green steel pilot projects planned. High carbon prices are a key catalyst behind this.
- Overall, the economic viability of green hydrogen is still some years away, although global interest in hydrogen is significantly increasing. The emergence of commercial green hydrogen is likely to occur this decade.
- Given the capital and infrastructure required to make commercial green steel, we are of the view, the electricity generation infrastructure required could mean that green steel will take at least a decade or more to commercialise.
- Therefore, metallurgical coal is likely to remain an important product for the Australian economy in the medium term.
- EAF using renewable power seems to be the future of the industry for the short to medium term, despite implications of scrap steel supply. EAF steelmaking has a lower carbon intensity to BOS steelmaking.

# MAP OF AUSTRALIAN HYDROGEN PROJECTS

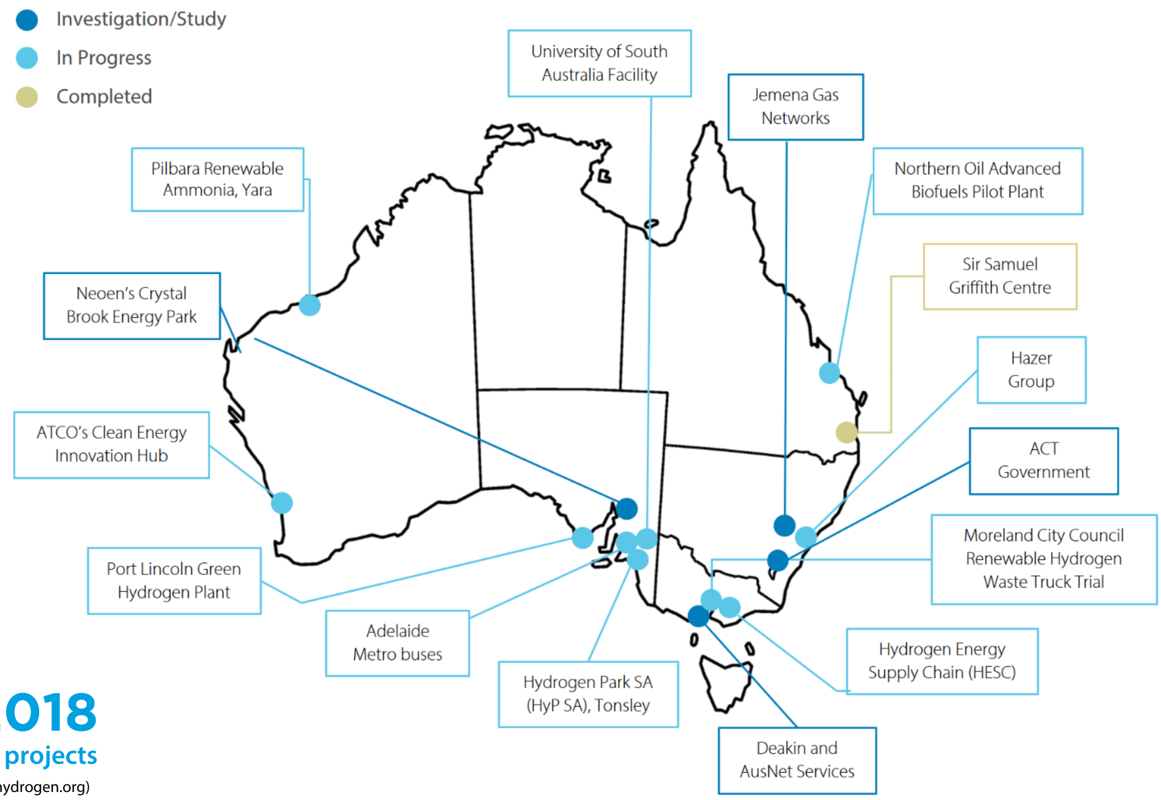
Research Paper

Author:
**Jessica Paterson, Christine Chen & Anthony O'Brien**

# HYDROGEN PROJECTS IN AUSTRALIA



**2021**
**76 projects**




**2018**
**15 projects**
(ieahydrogen.org)

# QLD HYDROGEN PROJECTS

**Source:** CSIRO - HyResource

| # | Project name | Key parties | Type of project | Location |
|---|---|---|---|---|
| # | **QLD** | | | |
| 1 | APA Renewable Methane Demonstration Project | APA Group, APT Facility Management Pty Ltd, Southern Green Gas | Hydrogen, Gas Networks | Wallumbilla |
| 2 | Hydrogen Park Gladstone | AGIG | Green Hydrogen | Gladstone |
| 3 | Renewable Hydrogen Production and Refuelling Project | BOC Limited, ITM Power Pty Ltd, Hyundai Motor Company Australia Pty Ltd | Green Hydrogen, Refuelling Station | Pinkenba |
| 4 | Queensland Nitrates Renewable Hydrogen and Ammonia Project | Queensland Nitrates Pty Ltd, Neoen Australia Pty Ltd | Hydrogen, Ammonia | Moura |
| 5 | Bundaberg Hydrogen Hub | Elvin Group Renewables, Denzo Pty Ltd, H2X, Plug Power | Hydrogen Mobility | Bundaberg |
| 6 | Green Liquid Hydrogen Export Project | Origin Energy, Kawasaki | Green hydrogen | Townsville |
| 7 | Julia Creek Project | QEM | Green Hydrogen, Shale & Vanadium Oil | Julia Creek |
| 8 | Queensland Solar Hydrogen Facility | Austrom Hydrogen | Green Hydrogen, Solar Battery | Port of Gladstone |
| 9 | Bio-Hydrogen Demonstration Plant | Southern Oil Refining Pty Ltd | Hydrogen from Waste Gases | Yarwun |
| 10 | Daintree Microgrid Project | Daintree Renewable Energy Pty Ltd | Hydrogen Storage, Solar Battery | Daintreee Rainforest |
| 11 | Central Queensland Hydrogen Project | Stanwell Corporation Ltd, Iwatani Corporation, Kawasaki Heavy Industries, Marubeni Corporation, Kansai Electric Power Company, APA Group | Hydrogen | Rockhampton |
| 12 | Dyno Nobel Renewable Hydrogen Project | Dyno Nobel Moranbah Pty Ltd, Incitec Pivot Ltd | Hydrogen | Moranbah |
| 13 | Edify Green Hydrogen Project | Edify Energy | Hydrogen | Townsville |
| 14 | Emerald Coaches Green Hydrogen Mobility Project | Emerald Coaches | Hydrogen Mobility | Emerald |
| 15 | Future Energy and Hydrogen Precinct | CleanCo | Hydrogen | Swanbank |
| 16 | Gibson Island Green Ammonia Feasibility | Fortescue Future Industries, Incitec Pivot Ltd | Hydrogen, Green Ammonia | Gibson Island |
| 17 | H2U Hub Gladstone | H2U | Hydrogen, Ammonia | Gladstone |
| 18 | Hay Point Hydrogen Project | Dalrymple Bay Infrastructure Ltd, North Queensland Bulk Ports Corporation, Brookfield Group, ITOCHU Corporation | Hydrogen Production, Hydrogen Storage | Hay Point |

# QLD, NSW & SA HYDROGEN PROJECTS

**Source:** CSIRO - HyResource

| # | Project name | Key parties | Type of project | Location |
|---|---|---|---|---|
| # | **QLD** | | | |
| 19 | Kogan Creek Renewable Hydrogen Demonstration Plant | CS Energy | Green Hydrogen, Solar Battery | Chinchilla |
| 20 | Renewable Hydrogen Powered Intercampus Transport | The University of Queensland | Hydrogen Mobility | Gatton |
| 21 | Rio Tinto Pacific Operations Hydrogen Program | Rio Tinto | Alumina | Gladstone |
| 22 | Sir Samuel Griffith Centre | Griffith University | Green Hydrogen, Solar Battery | Brisbane |
| 23 | Spicers Retreats Scenic Rim Trail Ecotourism Demonstration Using Low Pressure Hydrogen | Jilrift Pty Ltd | Microgrid | Clumber |
| 24 | Sumitomo Green Hydrogen Production Plant | Sumitomo Corporation, JGC Group | Green Hydrogen | Gladstone |
| 25 | SunHQ Hydrogen Park | Ark Energy Corporation | Hydrogen Mobility | Townsville |
| 26 | Utilitas-ReCarbon Organic Qaste to Green Hydrogen Technology | Utilitas Group, ReCarbon Inc., Bundaberg Regional Council | Hydrogen from Waste Gases | Bundaberg |
| # | **NSW** | | | |
| 27 | Western Sydney Green Gas Project | Jemena | Hydrogen Gas, Grid Generation | Horsley Park |
| 28 | Port Kembla Hydrogen Hub | Bluescope, Coregas | Hydrogen | Port Kembla |
| 29 | Hunter Hydrogen Hub | NSW Government | Hydrogen | Hunter Region |
| 30 | Manilla Solar & Renewable Energy Storage Project | Manilla Community Rnewable Energy Inc., Providence Asset Group | Hydrogen Storage, Solar Battery | Manilla |
| 31 | Port Kembla Hydrogen Refuelling Facility | Coregas | Refuelling Station, Hydrogen Mobility | Port Kembla |
| 32 | Port of Newcastle Hydrogen Hub Feasibility Study | Macquarie Green Investment Group, Port of Newcastle | Hydrogen | Port of Newcastle |
| 33 | Tallawarra B Dual Fuel Capable Gas/Hydrogen Power Plant | Energy Australia | Electricity Generation | Illawarra Region |
| # | **SA** | | | |
| 34 | Hydrogen Park SA (HyP SA) | AGIG, Siemens, SA Power Networks, KPMG | Green Hydrogen, Hydrogen Mobility | Tonsley |
| 35 | Eyre Peninsula Gateway Project - Demonstrator Stage | Worley, Hydrogen Utility (H2U) | Green Hydrogen, Ammonia | Eyre Peninsula |
| 36 | Neoen Australia Hydrogen Superhub (Crystal Brook Energy Park) | Neoen Australia Pty Ltd | Green Hydrogen | Crystal Brook |
| 37 | Santos' Moomba CCS project | Santos, BP | Blue Hydrogen, CCS | Moomba Gas Plant |
| 38 | Port Pirie Green Hydrogen Project | Trafigura Group Pte. Ltd, Nyrstart, South Australian Government | Green Hydrogen, Ammonia | Port Pirie |

# VIC, TAS & ACT HYDROGEN PROJECTS

**Source:** CSIRO - HyResource

| | Project name | Key parties | Type of project | Location |
|---|---|---|---|---|
| **#** | **VIC** | | | |
| 39 | Hydrogen Energy Supply Chain | Kawasaki Heavy Industries, AGL, J-Power, Iwatani, Marubeni, Sumitomo, Shell | Brown Hydrogen, Hydrogen Export | Latrobe Valley |
| 40 | Toyota Ecopark Hydrogen Demonstration | Toyota Motor Corporation Australia Limited | Hydrogen Mobility | Altona |
| 41 | Hydrogen Park Murray Valley | AGIG, ENGIE | Green Hydrogen | Wodonga |
| 42 | Portland Renewable Hydrogen Project | Countrywide Renewable Hydrogen Ltd, Glenelg Shire Council, Port of Portland | Green Hydrogen, Wind, Ammonia | Port of Portland |
| 43 | CSIRO Hydrogen Refuelling Station | CSIRO, Swinburne University of Technology | Hydrogen Mobility | Clayton |
| 44 | Geelong Hydrogen Hub | Geelong Port, CAC-H2 | Hydrogen, Ammonia | Corio Bay |
| 45 | Melbourne Hydrogen Hub | Countrywide Renewable Hydrogen Ltd, Melbourne Market Authority | Green Hydrogen, Solar | Epping |
| **#** | **TAS** | | | |
| 46 | CRH-Tasmania | Countrywide Renewable Hydrogen (CRH) | Green Hydrogen | Burnie |
| 47 | H2Tas Project | Woodside, Marubeni Corporation, IHI Corporation | Green Hydrogen, Ammonia | Bell Bay |
| 48 | Origin Tasmanian Green Hydrogen and Ammonia Plant | Origin Energy, Mitsui O.S.K. Lines | Green Hydrogen, Ammonia | Bell Bay |
| 49 | Fortescue Green Ammonia Plant | Fortescue Metals Group | Green Hydrogen, Ammonia | Bell Bay |
| 50 | ABEL Energy Bell Bay Powerfuels Project | ABEL Energy | Hydrogen, E-Methanol | Bell Bay |
| 51 | Grange Resources Study | Grange Resources (Tasmania) Pty Ltd | Hydrogen Gas | Burnie |
| **#** | **ACT** | | | |
| 52 | Hydrogen Test Facility - ACT Gas Network | Evoenergy, Canberra Institute of Technology | Hydrogen Gas | CIT Fischyk Campus |
| 53 | Renewable Hydrogen Refuelling Pilot | ACT Government, Neoen, ActewAGL, Hyundai, sgfleet | Refuelling Infrastructure | Canberra |

# WA HYDROGEN PROJECTS

**Source:** CSIRO - HyResource

| # | Project name | Key parties | Type of project | Location |
|---|---|---|---|---|
| | **WA** | | | |
| 54 | YURI Project/Yara Pilbara Renewable Ammonia | ENGIE, Yara | Green Hydrogen, Ammonia | Burrup |
| 55 | Clean Energy Innovation Hub | ATCO Australia Pty Ltd | Green Hydrogen, Microgrid | Jandakot |
| 56 | Clean Energy Innovation Park (CEIP) | ATCO Australia Pty Ltd | Green Hydrogen | Jandakot |
| 57 | Murchison Renewable Hydrogen Project | Hydrogen Renewables Australia, Copenhagen Infrastructure Partners | Green Hydrogen | Murchison |
| 58 | Asian Renewable Energy Hub (AREH) | NW Interconnected Power | Green Hydrogen, Ammonia | Port Hedland |
| 59 | Arrowsmith Hydrogen Project | Infinite Blue Energy, Xodus Group | Green Hydrogen, Hydrogen Mobility | Dongara |
| 60 | Kwinana Clean Fuels Hub | BP, Macquarie Capital | Green Hydrogen | Kwinana |
| 61 | Project GERI Feasibility Study | BP, GHD Group Ltd | Green Hydrogen, Ammonia | Geraldton |
| 62 | The Hazer Process; Commercial Demonstration Plant | Hazer Group Ltd | Hydrogen, Graphite | Woodman Point |
| 63 | Fortescue's Christmas Creek Iron Ore Mine | Fortescue, Hyzon | Hydrogen Mobility | Christmas Creek |
| 64 | Denham Hydrogen Demonstration Plant (WA) | Horizon Power | Hydrogen, Microgrid | Denham |
| 65 | Green Hydrogen for City of Cockburn | City of Cockburn | Hydrogen Mobility | Cockburn |
| 66 | Hybrid PV-Battery-Hydrogen System for Microgrids | Murdoch University | Hybrid Hydrogen-Battery Storage, Microgrid | Pilbara |
| 67 | Hyer Penetration - EDL Hydrogen Enabled Hybrid Renewables | Microgrid / regional applications | Green Hydrogen, Microgrid | Goldfields Esperance |
| 68 | Ord Hydrogen | Pacific Hydro Australia Development | Hydrogen, Ammonia | Kimberley |
| 69 | Renewable Hydrogen Ytansport Hub in the City of Mandurag | Hazer Group | Hydrogen Mobility | Peel |
| 70 | HyEnergy (Zero Carbon Hydrogen) | Province Resources, Ozexco Pty Ltd, Total Eren | Green Hydrogen | Glascoyne Region, Carnarvon |
| 71 | ATCO Hydrogen Blending Project | ATCO Gas Australia Pty Ltd | Hydrogen Gas | Jandakot |
| 72 | H2Perth | Woodside Energy Ltd | Green Hydrogen, Ammonia | Perth |
| 73 | Hydrogen Refueller Station Project | ATCO Gas Australia Pty Ltd, Fortescue Metals Group | Hydrogen Mobility | Jandakot |
| 74 | 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 |
| 75 | Preparing the Dampier to Bunbury Natural Gas Pipeline for Hydrogen | Dampier Bunbury Pipeline (AGIG) | Hydrogen Gas | Bunbury |
| 76 | Western Green Energy Hub | InterContinental Energy, CWP Global, Mining Green Energy Ltd | Green Hydrogen | Dundas, Kalgoorlie-Boulder |

# 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 Aus Govt. 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. BEV's 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 steel making 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 one 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 CO2from 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.
- **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 onto 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 intermediates 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.
- **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 renewables.

# 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) | $2.77778 \times 10^{-7}$ | 1 | $1 \times 10^{-6}$ |
| Megajoules (MJ) | 0.277778 | 1000000 | 1 |

| | Weight | | Gas | | Liquid | |
|---|---|---|---|---|---|---|
| | pounds (lb) | kilograms (kg) | cubic feet (scf) | cu meters (Nm3) | 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 Nm3gas | 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.
Nm3(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

| Parameter | Value |
|---|---|
| Hydrogen HHV (ΔH) | -286 kJ/mol |
| Hydrogen LHV (ΔH) | -242 kJ/mol |
| Energy content of 1 kg hydrogen | 141.9 MJ (HHV)<br>= 0.1419 GJ<br>= 39.4 kWh |
| | 120.1MJ (LHV)<br>= 0.1201 GJ<br>= 33.3 kWh |
| Energy content of 1 N-m3hydrogen | 12.7 MJ (HHV)<br>= 0.0127 GJ |
| Energy content of 1 gallon of gasoline | 121.3 MJ (LHV)<br>= 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)

## GENERALISED PRICING OF HYDROGEN PRODUCTION*

| $AUD/kg | $AUD/GJ |
|---|---|
| 1 | 8.34 |
| 2 | 16.68 |
| 3 | 25.02 |
| 4 | 33.36 |
| 5 | 41.70 |

*Pricing based on Hydrogen LHV

## GLOBAL COST OF GENERATION OF ALTERNATIVE ENERGY SOURCES (USD PER MWH)

| Source | Solar Utility Scale | Solar rooftop | Wind onshore | Wind offshore | Geothermal | Nuclear new | Nuclear extension | Hydro | Geothermal | Coal | Gas CC |
|---|---|---|---|---|---|---|---|---|---|---|---|
| NEA 2020 (at 7% discount rate | 56 | 126 | 50 | 88 | 100 | 68 | 32 | 72 | 99 | 88 | 71 |

NEA = Nuclear Energy Agency

# REFERENCES


1 CSIRO HyResource. (n.d.). *Hydrogen.* https://research.csiro.au/hyresource/about/hydrogen/#:~:text=As%20an%20energy%20 carrier%2C%20hydrogen ,as%20electricity%20using%20fuel%20cells

2 Blanco, H. (2015, July 22). *Hydrogen production in 2050: how much water will 74EJ need?*. Energypost.eu. https://energypost.eu/hydrogen-production-in-2050-how-much-water-will-74ej-need/

3 Australian Government Department of Industry, Science, Energy and Resources. (2021, June). *Resources and Energy Quarterly*. https://publications.industry.gov.au/publications/resourcesandenergyquarterlyjune2021/documents/Resources-and-Energy-Quarterly-June-2021-Gas.pdf

4 Tang, E., Wood, T., Brown, C., Casteel, M., Pastula, M., Richards, M., & Petri, R. (2018, March 31). *Solid Oxide Based Electrolysis and Stack Technology*. FuellCell Energy. https://www.osti.gov/servlets/purl/1513461

5 Advisian Pty Ltd. (2021, May 24). *Australia Hydrogen Market Study: Sector Analysis Summary.* https://www.cefc.com.au/media/nhnhwlxu/australian-hydrogen-market-study.pdf

6 CSIRO Energy & Futures. (2018). *National Hydrogen Roadmap: Pathways to an economically sustainable hydrogen industry in Australia*. www.csiro.au

7 US Office of Energy Efficiency & Renewable Energy. (n.d.). *DOE Technical Targets for Hydrogen Production from Electrolysis*. https://www.energy.gov/eere/fuelcells/doe-technical-targets-hydrogen-production-electrolysis

8 Australian Government. (2021). *Australia's Long-Term Emissions Reduction Plan: A whole-of-economy Plan to achieve net zero emissions by 2050*. https://www.industry.gov.au/sites/default/files/October%202021/document/australias-long-term-emissions- reduction-plan.pdf

9 Australian Renewable Energy Agency (ARENA). (2020, November 30). *Australia's pathway to $2 per kg hydrogen*. Arenawire. https://arena.gov.au/blog/australias-pathway-to-2-per-kg-hydrogen/

10 Hydrogen Council. (2020, January 20). *Path to hydrogen competitiveness: A cost perspective.* https://hydrogencouncil.com/wp-content/uploads/2020/01/Path-to-Hydrogen-Competitiveness_Full-Study-1.pdf

11 International Energy Agency (IEA). (2021, November). *Hydrogen Tracking Report 2021 - Global Hydrogen Demand by* Sector. https://www.iea.org/reports/hydrogen

12 Australian Renewable Energy Agency (ARENA) & Acil Allen Consulting. (2018, August). *Opportunities for Australia from Hydrogen Exports*. https://arena.gov.au/assets/2018/08/opportunities-for-australia-from-hydrogen-exports.pdf

13 IEA. (2019, November 22) *Transport sector CO2 emissions by mode in the Sustainable Development Scenario, 2000-2030* https://www.iea.org/data-and-statistics/charts/transport-sector-co2-emissions-by-mode-in-the-sustainable-development-scenario-2000-2030

14 US Office of Energy Efficiency & Renewable Energy. (n.d.). *Hydrogen Pipelines.* https://www.energy.gov/eere/fuelcells/hydrogen-pipelines

15 Australian Gas Infrastructure Group (AGIG). (2021, May 19). *Hydrogen Park South Australia Opens for Business.* https://www.agig.com.au/media-release---hyp-sa-official-opening

16 Farmer, M. (2020, July 21). *What Colour is your Hydrogen? A Power Technology jargon-buster.* Power Technology. https://www.power-technology.com/features/hydrogen-power-blue-green-grey-brown-extraction-production- colour-renewable-energy-storage/

17 Higman, C. (2016, October 19). *State of the Gasification Industry*. Higman Consulting GmbH. https://www.netl.doe.gov/sites/default/files/2021-04/2016-Wed-Higman.pdf

18 Global Syngas Technologies Council. (n.d.). *Steam-Methane Reforming.* https://globalsyngas.org/syngas-technology/syngas-production/steam-methane-reforming/

19 International Energy Agency (IEA). (2020, June). *Tracking Hydrogen 2020: Low-carbon Hydrogen production is ramping up, especially using electrolysis.* https://www.iea.org/reports/tracking-hydrogen-2020

20 International Energy Agency (IEA). (2021, November). *Hydrogen Tracking Report 2021: Water Electrolysis.* https://www.iea.org/reports/hydrogen

21 CSIRO HyResource. (2020, December 17). *A Short Report on Hydrogen Industry Policy Initiatives and the Status of Hydrogen Projects.* https://research.csiro.au/hyresource/a-short-report-on-hydrogen-industry-policy-initiatives-and-the-status-of- hydrogen-projects/

22 US Office of Energy Efficiency & Renewable Energy. (n.d.). *Hydrogen Production: Electrolysis.* https://www.energy.gov/eere/fuelcells/hydrogen-production-electrolysis

23 Barrett, A. (2022, January 30). *Tech Q of the Week: The Hydrogen Color Scale.* http://utahcleancities.org/tech-q-week-hydrogen-color/#/find/nearest

24 Gandolfi, A., Patel, A., et al. (2020, September 22). Green Hydrogen: The next transformational driver of the Utilities Industry. Goldman Sachs https://www.goldmansachs.com/insights/pages/gs-research/green-hydrogen/report.pdf

25 IEA. (2021, December 1). *Could the green hydrogen boom lead to additional renewable capacity by 2026?.* https://www.iea.org/articles/could-the-green-hydrogen-boom-lead-to-additional-renewable-capacity-by-2026

26 Cummins Inc. (n.d.). *Electrolysis* https://www.cummins.com/new-power/applications/about-hydrogen/electrolysis

27 CSIRO. (n.d.). *Alkaline Electrolysis.* https://www.csiro.au/en/work-with-us/ip-commercialisation/hydrogen-technology-marketplace/alkaline-electrolysis

28 Janssen, D. (2020, August 28). *Europe, China battle for global supremacy on electrolyser manufacturing*. EURACTIV.com. https://www.euractiv.com/section/energy/news/europe-china-battle-for-global-supremacy-on-electrolyser-manufacturing/

29 Skoczylas, T. (2021, March 10). *Water Electrolysers for Applications of Green Hydrogen*. Nel Hydrogen, & Chile Ministerio de Energia. https://www.capitalenergetico.cl/wp-content/uploads/2021/03/Nel-H2_Chile_r1.pdf

30 Air Liquide. (2021, February 08). *Inauguration of the world's largest PEM electrolyser to produce decarbonized hydrogen.* https://www.airliquide.com/magazine/energy-transition/inauguration-worlds-largest-pem-electrolyzer

31 Linde. (2021, January 13). *Linde to Build, Own and Operate World's Largest PEM Electrolyzer for Green Hydrogen.* https://www.linde.com/news-media/press-releases/2021/linde-to-build-own-and-operate-world-s-largest-pem-electrolyzer-for-green-hydrogen

32 TOTALEnergies. (2021, January 13). *Total and Engie partner to develop France's largest site for the production of green hydrogen from 100% renewable electricity.* https://totalenergies.com/media/news/press-releases/total-and-engie-to-develop-france-s-largest-site-of-green-hydrogen

33 Nel Hydrogen. (n.d.). *Water Electrolysers/hydrogen generators*. https://nelhydrogen.com/water-electrolysers-hydrogen-generators/

34 Lichner, C. (2020, March 26). Electrolyzer overview: Lowering the cost of hydrogen and distributing its production. PV Magazine USA. https://pv-magazine-usa.com/2020/03/26/electrolyzer-overview-lowering-the-cost-of-hydrogen-and-distributing-its-productionhydrogen-industry-overview-lowering-the-cost-and-distributing-production/

35 International Renewable Energy Agency (IRENA). (2021, June). Renewable Power Generation Costs in 2020. https://www.irena.org/publications/2021/Jun/Renewable-Power-Costs-in-2020

36 International Energy Agency (IEA). (2021, November 30). *LCOE of utility-scale solar PV and onshore in 2020 and in the high commodity price scenario.* https://www.iea.org/data-and-statistics/charts/lcoe-of-utility-scale-solar-pv-and-onshore-in-2020-and-in-the-high-commodity-price-scenario

37 Longden T., Jotzo F., Prasad M., & Andrews, R. (2020, August). *Green hydrogen production costs in Australia: implications of renewable energy and electrolyser costs.* CCEP Working Paper 20-07, ZCEAP Working Paper ZCWP03-20. The Australian National University. https://energy.anu.edu.au/files/2020%2009%2001%20-%20ZCEAP%20-%20CCEP%20 Working%20Paper%20-%20Green%20hydrogen%20production%20costs.pdf

38 International Energy Agency (IEA). (2019, June). *The Future of Hydrogen: Seizing today's opportunities.* https://www.iea.org/reports/the-future-of-hydrogen

39 PhosphatePrice.com. (2020, August 29). *Electrolyser Manufacturing: Europe & China Are Locked in Battle for Global Supremacy* https://phosphateprice.com/electrolyser-manufacturing-europe-china-are-locked-in-battle-for-global-supremacy/

40 Bruce, S., Temminghoff, M., Hayward, J., Schmidt, E., Munnings, C., Palfreyman, D., & Hartley P. (2018). *National Hydrogen Roadmap*. CSIRO, Australia. https://www.csiro.au/en/work-with-us/services/consultancy-strategic-advice-services/csiro-futures/futures-reports/hydrogen-roadmap

41 Franke, A. (2021, March 22). *Siemens Energy targets $1.50/kg renewable hydrogen cost by 2025.* S&P Global. https://www.spglobal.com/platts/en/market-insights/latest-news/electric-power/032221-siemens-energy-targets-150kg-renewable-hydrogen-cost-by-2025

42 Head, B. (2021, March 29). *Blue skies for green hydrogen demand*. Australian Financial Review. https://www.afr.com/companies/energy/blue-skies-for-green-hydrogen-demand-20210323-p57dg0

43 Ho, K. (2020, June 18). *How to build an electrolyser.* Energy Magazine. https://www.energymagazine.com.au/the-future-of-hydrogen-how%E2%80%8C-%E2%80%8Cto%E2%80%8C-%E2%80%8Cbuild%E2%80%8C-%E2%80%8Can%E2%80%8C-%E2%80%8Celectrolyser/

44 Yin, I. (2021, December 06). *China scaling up electrolyser manufacturing base for domestic, export markets.* S&P Global. https://www.spglobal.com/platts/en/market-insights/latest-news/energy-transition/120621-china-scaling-up-electrolyzer-manufacturing-base-for-domestic-export-markets

45 European Commission. (2020, July 08). *COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT A hydrogen strategy for a climate-neutral Europe.* Brussels, COM(2020) 301 Final. https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf

46 Wood Mackenzie. (2019, October 25). *Energy Transition: The future for green hydrogen.* https://www.woodmac.com/news/editorial/the-future-for-green-hydrogen/

47 ARENA. *Annual Report 2020-2021.* https://arena.gov.au/assets/2020/06/arena-annual-report-20-21.pdf

48 Hydrogen Council. (2017, November). *Hydrogen scaling up: A sustainable pathway for the global energy transition.* https://hydrogencouncil.com/wp-content/uploads/2017/11/Hydrogen-scaling-up-Hydrogen-Council.pdf

49 Australian Government Department of Industry, Science, Energy and Resources. (n.d.). *Growing Australia's hydrogen industry: Partnering internationally to supply hydrogen.* https://www.industry.gov.au/policies-and-initiatives/growing-australias-hydrogen-industry

50 Australian Government Department of Industry, Science, Energy and Resources. (2021, December). State of Hydrogen 2021.https://www.industry.gov.au/data-and-publications/state-of-hydrogen-2021/hydrogen-industry-development

51 McMaugh, S. (n.d.). *Budget Review 2021-22: Emissions reduction and hydrogen.* Parliament of Australia. https://www.aph.gov.au/About_Parliament/Parliamentary_Departments/Parliamentary_Library/pubs/rp/BudgetReview202122/EmissionsReductionHydrogen

52 Farkas-Mills, N., & Singh, A. (2020).*Investing in hydrogen: Ready, set, net zero.* Deloitte UK. https://www2.deloitte.com/content/dam/Deloitte/uk/Documents/energy-resources/deloitte-uk-energy-resources-investing-in-hydrogen.pdf

53 Parks, G., Boyd, R., Cornish, J., & Remick, R. (2014, May).*Hydrogen Station Compression, Storage, and Dispensing Technical Status and Costs.* National Renewable Energy Laboratory (NREL) for the US Department of Energy Hydrogen and Fuel Cells Program. https://www.nrel.gov/docs/fy14osti/58564.pdf

54 Taibi, E., Blanco, H., Miranda, R., & Carmo, M. (2020). *Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5$^0$C Climate Goal.* International Renewable Energy Agency (IRENA). https://irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf

55 Brown, A. (2019, May 30). *Hydrogen Transport.* The Chemical Engineer. https://www.thechemicalengineer.com/features/hydrogen-transport/

56 Edison Investment Research Limited. (2020). *Finding the sea of green – The opportunity and options for shipping green H2.* https://www.edisongroup.com/investment-themes/finding-the-sea-of-green-the-opportunity-and-options-for-shipping-green-h2/

57 Kariya, D., & Komiya, T. (2020). *Accommodating the Energy Supply Needs of the Next Era: Kawasaki's Hydrogen* Liquefaction System. Kawasaki Heavy Industries Ltd. https://global.kawasaki.com/en/scope/pdf_e/scope114_03.pdf

58 Andersson, J., & Grönkvist, S. (2019, May 3). *Large-scale storage of hydrogen.* International Journal of Hydrogen Energy, Volume 44, Issue 23, Pages 11901-11919. https://doi.org/10.1016/j.ijhydene.2019.03.063

59 Parfomak, P. (2021, March 2). *Pipeline Transportation of Hydrogen: Regulation, Research, and Policy.* Congressional Research Service. https://www.everycrsreport.com/files/2021-03-02_R46700_294547743ff4516b1d562f7c4dae166186f1833e.pdf

60 Melaina, M., Antonia, O., & Penev, M. (2013, March). *Blending Hydrogen into Natural Gas Pipeline Networks: A* Review of Key Issues. National Renewable Energy Laboratory (NREL). https://www.nrel.gov/docs/fy13osti/51995.pdf

61 Energy Networks Australia & GPA Engineering Pty Ltd. (2021, August 13). *Technical and Commercial Review of Infrastructure Victoria's Gas Infrastructure Interim Report.* https://www.energynetworks.com.au/miscellaneous/technical-and-commercial-review-of-infrastructure-victorias-gas-infrastructure-interim-report-gpa-engineering/

62 Australia Government Department of Industry, Science, Energy and Resources. (2021, June 21). *A Hydrogen Guarantee of Origin scheme.* https://consult.industry.gov.au/hydrogen-guarantee-of-origin-scheme

63 ARUP Australia Pty Ltd. (2019, November). *Australian Hydrogen Hubs Study: Technical Study.* COAG Energy Council Hydrogen Working Group, Issue 2. https://verdantearthtechnologieslimited.com/verdant-new-site/wp-content/uploads/2021/08/nhs-australian-hydrogen-hubs-study-report-2019.pdf

64 Menon, E. (2015). *Pipeline Economics.* https://www.sciencedirect.com/topics/engineering/right-of-way

65 Kawasaki Heavy Industries Ltd. (2019, December 11). *World's First Liquefied Hydrogen Carrier SUISO FRONTIER Launches Building an International Hydrogen Energy Supply Chain Aimed at Carbon-free Society.* https://global.kawasaki.com/en/corp/newsroom/news/detail/?f=20191211_3487

66 International Energy Agency (IEA). (2021, November). *Global Hydrogen Review 2021.* https://iea.blob.core.windows.net/assets/5bd46d7b-906a-4429-abda-e9c507a62341/GlobalHydrogenReview2021.pdf

67 Queensland Transport and Logistics Council. (2020, September). *Submissions: Inland Rail EOI.* https://www.qtlc.com.au/hydrogen/hydrogen-submissions/

68 Zogopoulos, E. (2020, July 10). *Hydrogen: Is this the future? (Part II).* Energy Industry Review. https://energyindustryreview.com/analysis/hydrogen-is-this-the-future-part-ii/

69 Climate CH2ampion. (n.d.). *How Does Hydrogen Benefit Transport?.* https://www.climatech2ampion.org/pocket-guides/how-does-hydrogen-benefit-transport/

70 Stevens, P. (2019, December 30). *The battery decade: How energy storage could revolutionize industries in the next 10 years.* CNBC. https://www.cnbc.com/2019/12/30/battery-developments-in-the-last-decade-created-a-seismic-shift-that-will-play-out-in-the-next-10-years.html

71 Rivard, E. & Trudeau, M. (2019). Hydrogen Storage for Mobility. Issue 12. https://www.mdpi.com/1996-1944/12/12/1973/pdf

72 Kane, M. (2020, March 28). *Battery Electric v Hydrogen Fuel Cell: Efficiency Comparison.* InsideEvs. https://insideevs.com/news/406676/battery-electric-hydrogen-fuel-cell-efficiency-comparison/

73 Leachman, J. (2017, March 17). *So just how dangerous is hydrogen fuel?.* Washington State University. https://hydrogen.wsu.edu/2017/03/17/so-just-how-dangerous-is-hydrogen-fuel/

74 US Office of Energy Efficiency & Renewable Energy. (n.d.). *Safe Use of Hydrogen.* https://www.energy.gov/eere/fuelcells/safe-use-hydrogen

75 US Department of Energy. (n.d.). *Hydrogen Basics.* Office of Energy Efficiency & Renewable Energy Alternative Fuels Data Centre (AFDC) https://afdc.energy.gov/fuels/hydrogen_basics.html

76 Community Environment Council (CEC). (n.d.). *Fuel Cell Electric Vehicles: Why Fuel Cell Electric Vehicles Matter.* https://resource.cecsb.org/fcev/

77 Henley, C., & Hogard, P. (2021, October 08). T*oyota Mirai Sets GUINNESS WORLD RECORDS™ Title with 845 Mile Zero Emission Journey.* Toyota Newsroom https://pressroom.toyota.com/toyota-mirai-sets-guinness-world-records-title-with-845-mile-zero-emission-journey/

78 Bureau of Infrastructure and Transport Research Economics (BITRE). (2021, January). *Trainline 8: Statistical Report.* Australian Government Department of Infrastructure, Transport, Regional Development and Communications. https://www.bitre.gov.au/sites/default/files/documents/train_008.pdf

79 Townsend, A., Jiya, I., Martinson, C., Bessarabov, C., Gouws, R. (2020, November). *A comprehensive review of energy sources for unmanned aerial vehicles, their shortfalls and opportunities for improvements.* Heliyon Volume 6, Issue 11. https://doi.org/10.1016/j.heliyon.2020.e05285. https://www.sciencedirect.com/science/article/pii/S2405844020321289

80 Hoelzen, J., Silberhorn, D., Zill, T., Bensmann, B., Hanke-Rauschenbach, R. (2022, January 15). *Hydrogen-powered aviation and its reliance on green hydrogen infrastructure – Review and research gaps.* International Journal of Hydrogen Energy Volume 47, Issue 5, Pages 3108-3130. https://doi.org/10.1016/j.ijhydene.2021.10.239 https://www.sciencedirect.com/science/article/pii/S0360319921043184

81 ENERGIA. (2018, May). *Australian Electric Vehicle Market Study.* Prepared for Australian Renewable Energy Agency (ARENA) & Clean Energy Finance Corp (CEFC). https://arena.gov.au/assets/2018/06/australian-ev-market-study-report.pdf

82 Global CCS Institute. *What is CCS?.* https://www.globalccsinstitute.com/about/what-is-ccs/

83 Global CCS Institute. *Capturing carbon dioxide (CO2).* https://www.globalccsinstitute.com/about/what-is-ccs/capture/

84 Beck, L., & Temple-Smith, L. (2020, May 30). *Is CCS expensive?.* Global CCS Institute. https://www.globalccsinstitute.com/resources/publications-reports-research/is-ccs-expensive/

85 Bright, M. (2020, December 03). *The Science-Based Case for CCUS.* Third Way. https://www.thirdway.org/memo/the-science-based-case-for-ccus

86 Global CCS Institute. (2011). *Zero emissions platform: The Costs of CO2 Capture, Transport and Storage.*

87 Global CCS Institute. (n.d.). *Transport.* https://www.globalccsinstitute.com/about/what-is-ccs/transport/

88 Global CCS Institute. (2019). *The Global Status of CCS: 2019.* https://www.globalccsinstitute.com/resources/global-status-report/previous-reports/

89 Global CCS Institute. (2016, June). *Global Status of CCS: Special Report – Understanding Industrial CCS Hubs and Clusters.* www.globalccsinstitute.com/wp-content/uploads/2019/08/Understanding-Industrial-CCS-hubs-and-clusters.pdf

90 Global CCS Institute. (2021). *Global Status of CCS 2021.* https://www.globalccsinstitute.com/wp-content/uploads/2021/11/Global-Status-of-CCS-2021-Global-CCS-Institute-1121.pdf

91 European Commission. (2016). *The EU Emissions Trading System (EU ETS).* https://ec.europa.eu/clima/system/files/2016-12/factsheet_ets_en.pdf

92 European Commission Climate Action. (2015, November 18). Report on review of Directive 2009/31/EC on the geological storage of carbon dioxide. Brussels, COM(2015) 576 Final. https://doi.org/10.2834/9801. https://ec.europa.eu/clima/eu-action/carbon-capture-use-and-storage/legal-framework-safe-geological-storage-carbon-dioxide_en

93 Havercroft, I. (2018). *Thought Leadership Report: CCS Legal and Regulatory Indicator (CCS-LRI).* https://www.globalccsinstitute.com/archive/hub/publications/202111/ccs-legal-and-regulatory-indicatorglobal-ccs-institute-2018digital.pdf

94 Blain, L. (2021, July 20). *World's 2nd-largest steel producer to begin making green steel by 2025.* New Atlas. https://newatlas.com/energy/arcelormittal-green-steel-hydrogen/

95 Sander-Green, L. (2020, June 1). *Do we really need Coal to make Steel?.* Wildsight. https://wildsight.ca/2020/06/01/do-we-really-need-steelmaking-coal/

96 Eckert, V. (2020, June 25). *ArcelorMittal seeks EU support to make steel greener.* Thomson Reuters https://www.reuters.com/article/us-arcelormittal-carbon-idUSKBN23W1W9

97 Australian Government Geoscience Australia. (2021). *Coal AECR 2021.* https://www.ga.gov.au/digital-publication/aecr2021/coal

98 Hoffman, C., Van Hoey, M., & Zeumer, B. (2020, April). Decarbonization challenge for steel: Hydrogen as a solution in Europe. McKinsey & Company. https://www.mckinsey.com/~/media/McKinsey/Industries/Metals%20and%20Mining/Our%20Insights/Decarbonization%20challenge%20for%20 steel/Decarbonization-challenge-for-steel.pdf

99 World Steel Association. (2021, April). *Fact Sheet: Steel and raw materials.* https://www.worldsteel.org/en/dam/jcr:16ad9bcd-dbf5-449f-b42c-b220952767bf/fact_raw+materials_2018.pdf

100 Wood, T., Dundas, G., and Ha, J. (2020, May). *Start with steel: A practical plan to support carbon workers and cut* emissions. Grattan Institute. https://grattan.edu.au/wp-content/uploads/2020/05/2020-06-Start-with-steel.pdf

101 Sullivan, L. (2021, August 25). *Renewable Biomass Offers Numerous Benefits for Hydrogen Producers.* https://www.forest2market.com/blog/renewable-biomass-offers-numerous-benefits-for-hydrogen-producers

102 CEIC Data. (n.d.). *Australian Coal Production 1981-2020.* https://www.ceicdata.com/en/indicator/australia/coal-production

103 Australian Government Department of Industry, Science, Energy, and Resources. (2021, December). *Resources* and Energy Quarterly. https://publications.industry.gov.au/publications/resourcesandenergyquarterlydecember2021/index.html

104 Minerals Council of Australia. (n.d.). *Coal: building Australia's future.* https://www.minerals.org.au/coal-building-australias-future

105 Pan, S., & Zhao, T. (2021, December 08). *China decarbonization could create graphite electrode shortage amid more EAF steelmaking*. Fastmarkets. https://www.fastmarkets.com/insights/china-decarbonization-could-create-graphite-electrode-shortage-amid-more-eaf-steelmaking

106 The Australian Worker's Union. (2020, March 26). *Classify the Steel Industry as Essential.* https://www.awu.net.au/news/2020/03/10851/classify-the-steel-industry-as-essential/

107 Hee Han, N. (2021, April 15). *Covid-19 and the Steel Industry: Presentation at ISS 2021.* World Steel Association. https://www.worldsteel.org/en/dam/jcr:3ac2475c-7d51-4a9b-8e7f-bf0aefbaf63d/ISS_15%2520April%25202021_Nae%2520Hee%2520Han.pdf

# KEY CONTRIBUTORS

If you have any specific questions, please contact the contributors below.

**John Hirjee**
Executive Director – Resources, Energy & Infrastructure
E: John.Hirjee@anz.com

**Jessica Paterson**
Graduate - Resources, Energy & Infrastructure, R&A
E: Jessica.Paterson@anz.com

**Maggie Cai**
Analyst - Group Mergers & Acquisitions
E: Maggie.Cai@anz.com

**Sharon Klyne**
Associate Director - Institutional Communications
E: Sharon.Klyne@anz.com

**With special thanks to....**
James Borg, Julia Byron, Bonny Cheng, Christine Chen, Sarah Howell, Robyn Johnston, Emma Myers, Rhys Murray, Anthony O'Brien, Sachiko Robinson, Elizabeth Rudall, Clare Rodricks, Stephen Toohey, Shane White and Steven Wong.

## IMPORTANT NOTICE

anz.com/institutional/