THE ANZ HYDROGEN HANDBOOK VOL II

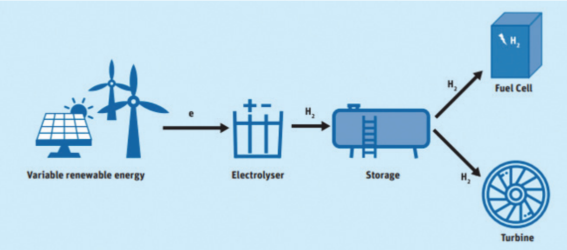
END USES

HYDROGEN END USES

PURE HYDROGEN

LARGE SCALE ELECTRICITY GENERATION

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



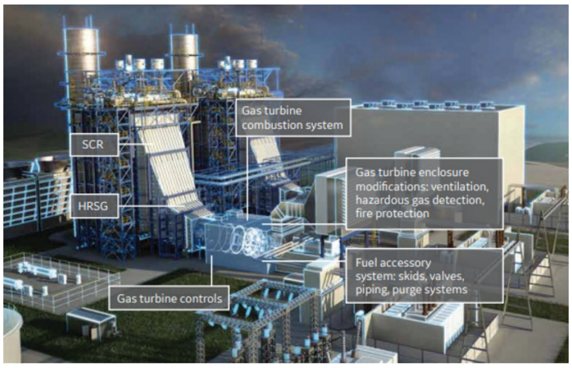
Large scale hydrogen-based electricity generation pathways (csiro.au)

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

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

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

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



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

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

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

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

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

GAS BLENDING

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

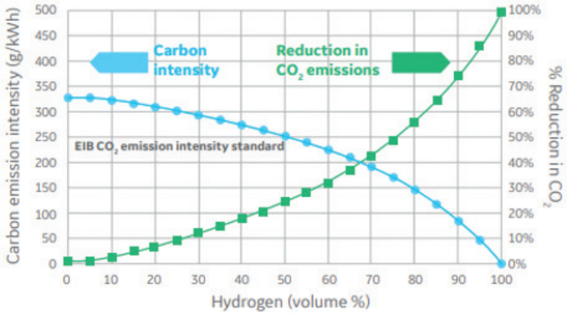
Australia – Operational Hydrogen Gas Blending Projects	
Clean Energy Innovation Hub – ATCO	H_2 produced from electrolyser powered by solar energy. H_2 production distributed into a demonstration facility, consisting of a microgrid including a display home and 200kW gas generator. Blending volume target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

Source: CSIRO – HyResource

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

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

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



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

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

HARD TO ABATE GEOGRAPHIES AND SECTORS

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

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

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

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

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

MOBILITY & FUEL CELLS

HYDROGEN-BASED TRANSPORTATION

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

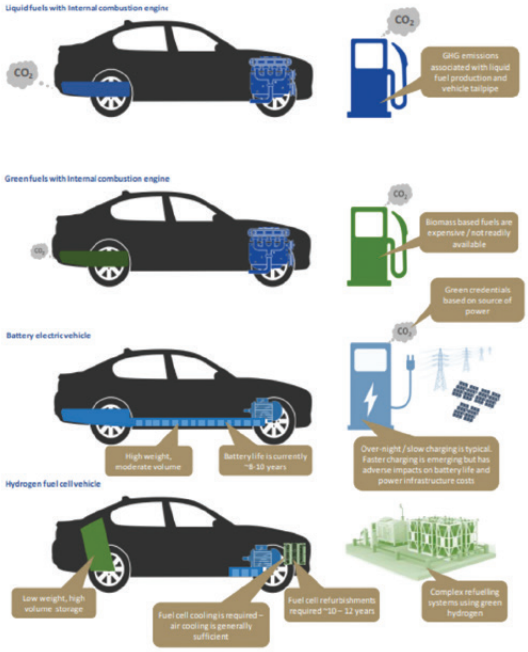
H_2 can be used in fuel cells to efficiently generate electricity for an electric vehicle, or can be converted into a denser form (such as ammonia, methanol and synthetic fuel) for use in ICEs. Unlike in some sectors, H_2 already has a decarbonised competitor in lithium-ion batteries. Battery costs have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

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

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

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

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



Differences between vehicle technologies (cefc.com.au)

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

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

Safety

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

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

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

TRANSPORTATION USE CASES

Material handling

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

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

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

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

Heavy-duty vehicles

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

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

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

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

Rail

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

Ferries

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

Maritime

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

Aviation

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

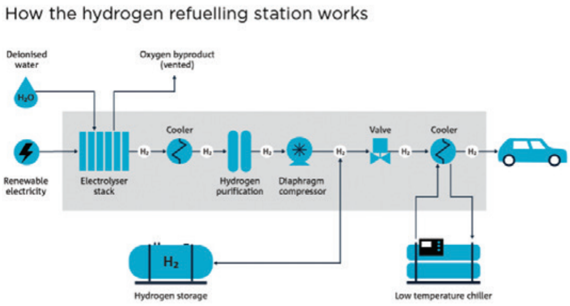
In terms of manned aircraft/passenger aviation, application of fuel cells to this sector appears to be quite distant given the current energy requirements. That said, there is potential for regional flights (20-80pax, within a 1000km range) to make use of electrically-driven turbo props.[152] At this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

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

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

INFRASTRUCTURE REQUIREMENTS

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



A refuelling station (csiro.au)

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

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

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

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

COST CHALLENGES

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

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

The cost of the fuel cell stack

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

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

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

The cost of on-board storage

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

COMPONENT MANUFACTURERS

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

HYDROGEN-BASED FUELS

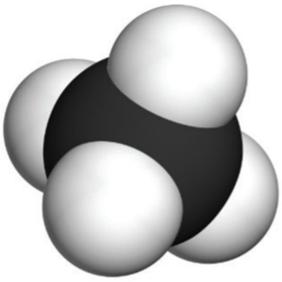
Hydrogen-based fuels include derivative products such as synthetic methane, ammonia and methanol. Interestingly, 60% and 30% of the 53Mt of H_2 used in industry during 2022 was for ammonia and methanol production respectively. Almost all of this H_2 was grey.[166]

SYNTHETIC METHANE

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

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

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



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

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

AMMONIA

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

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

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

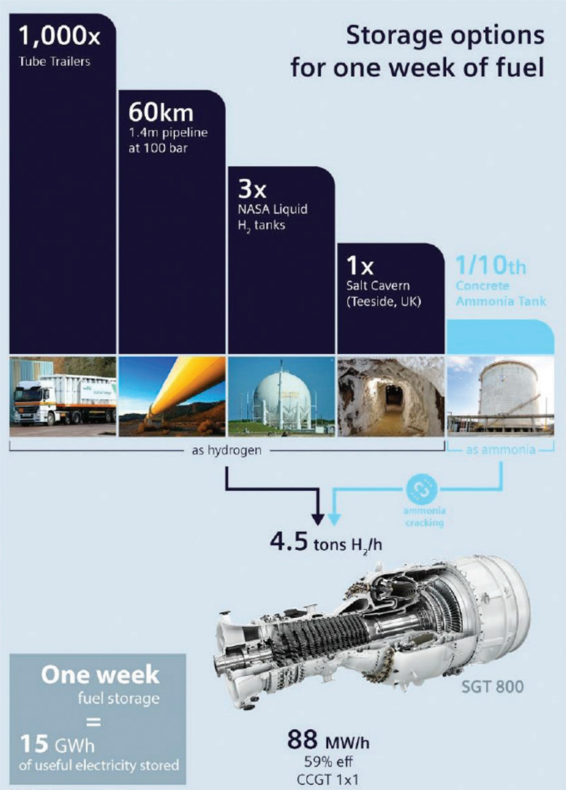
Ammonia can be created via the Haber-Bosch process which involves combining nitrogen gas with hydrogen at high temperatures and pressures. The hydrogen storage capability of ammonia is significant given that it is 17.6% hydrogen by weight.[171] The H_2 component of ammonia can be extracted by heating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

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

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

Source: University of Pennsylvania – Kleinman Center for Energy Policy

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



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

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

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

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

METHANOL

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

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

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

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

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

BIOFUELS

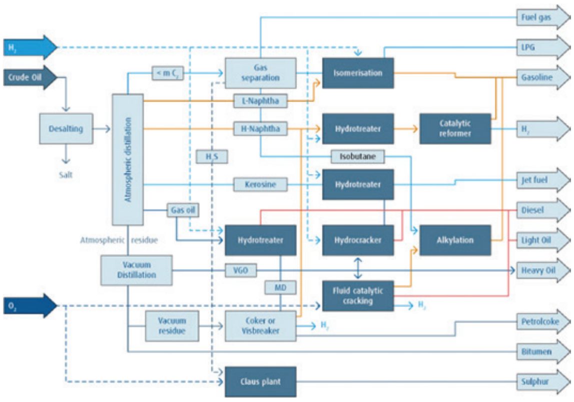
HYDROGEN IN THE REFINERY PROCESS

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

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

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

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



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

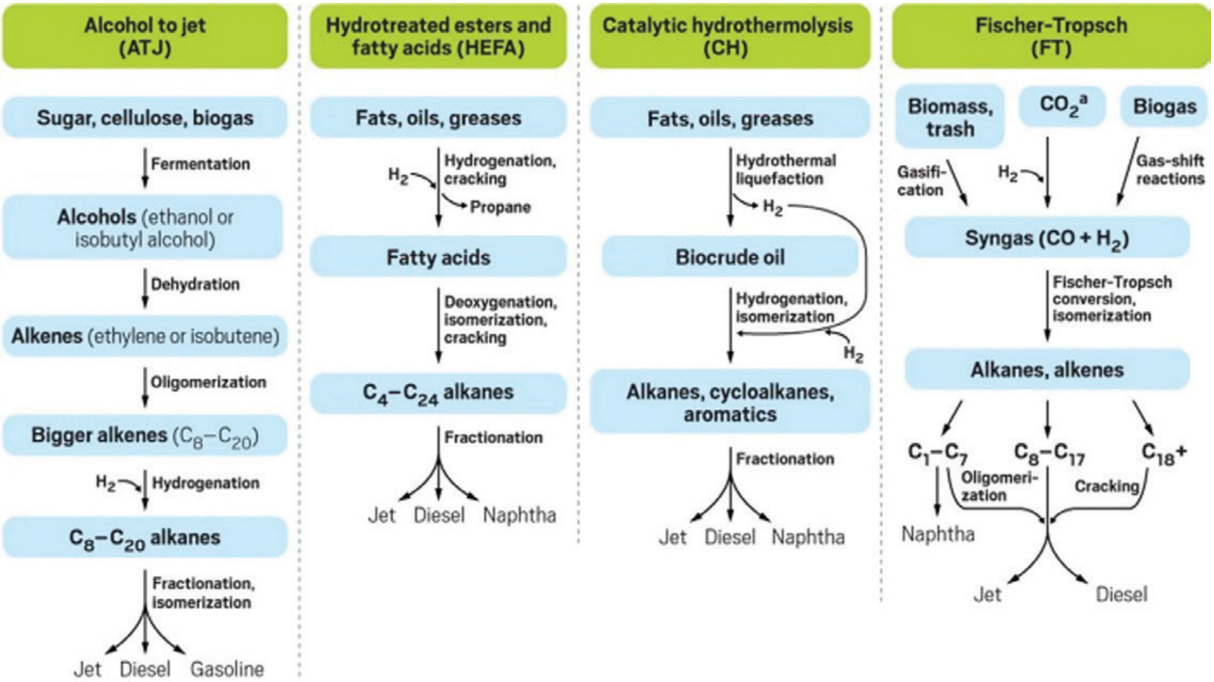
PRODUCING BIOFUELS WITH HYDROGEN

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

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

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

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



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

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

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

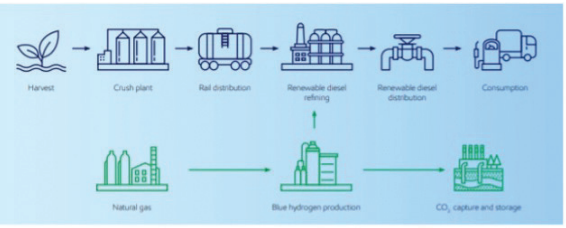


Diagram of ExxonMobil’s renewable diesel production process at the Strathcona refinery (exxonmobil.com)

BIOFUELS FOR HARD TO ABATE SECTORS

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

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

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

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

GREEN STEEL

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

CONVENTIONAL STEELMAKING TECHNOLOGY

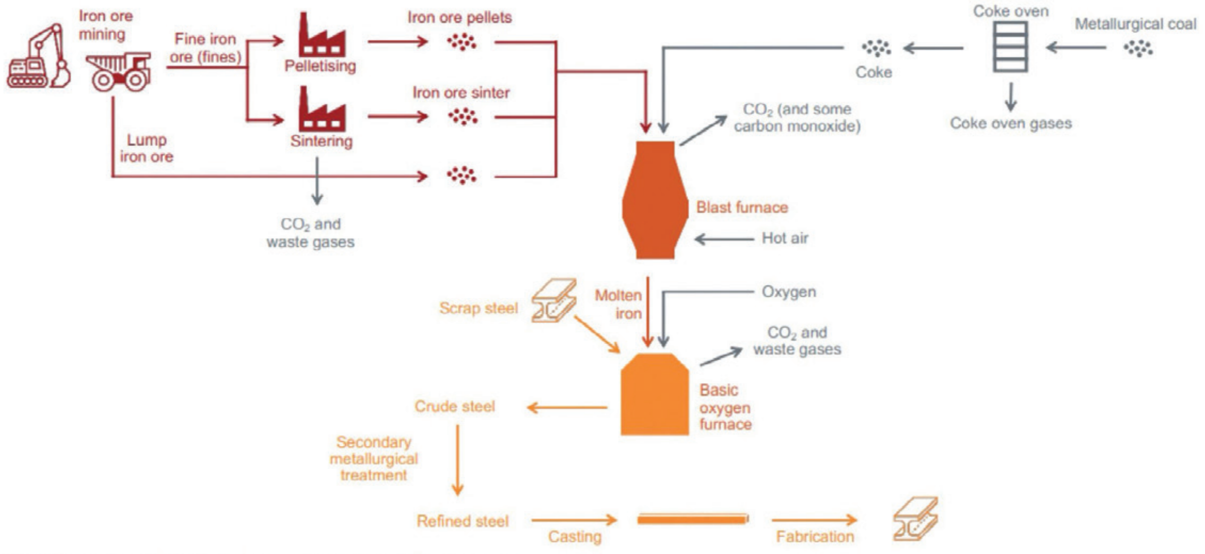
Primary steelmaking has two methods: BOF (Basic Oxygen Furnace or Blast Furnace) and the EAF (Electric Arc Furnace). Global steel production comprises 70% via BOF and 30% via EAF.[205]

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

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

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

Figure A.1: Integrated steel-making



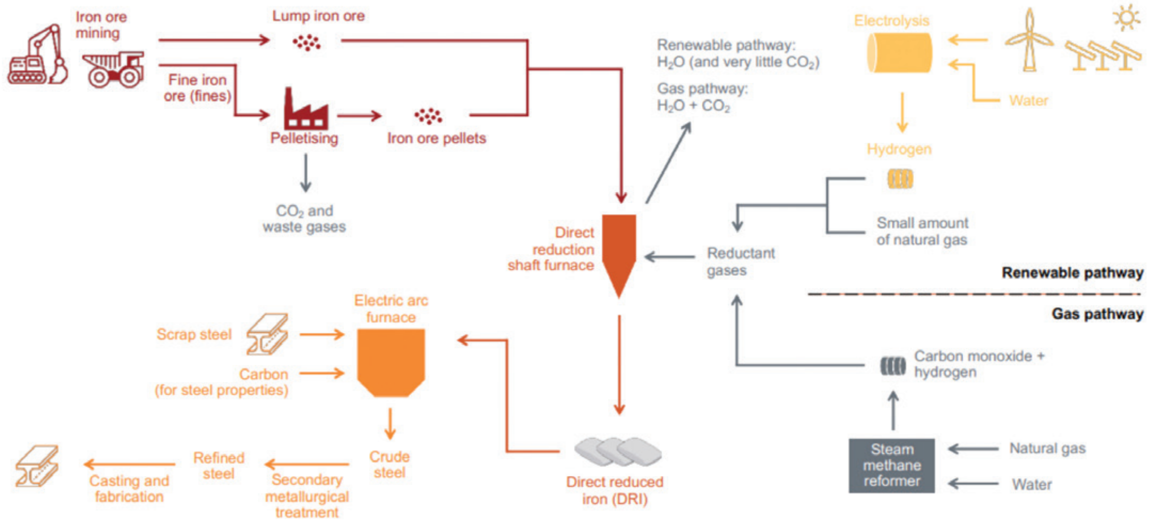
Note: Scrap steel is added to the basic oxygen furnace to control the temperature.
Source: Grattan analysis. Some icons sourced from flaticon.com (2020).

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

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

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

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



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

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

HYDROGEN-BASED STEELMAKING

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

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

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

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

GREEN STEEL EXPORT PATHWAYS

Green steel export pathways are inclusive of[217]:

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

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

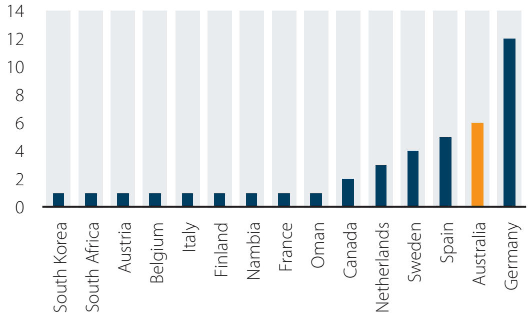
(3) Pathway 3 - Export the ore and hydrogen overseas for steel- making.

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

GREEN STEEL PROJECTS

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

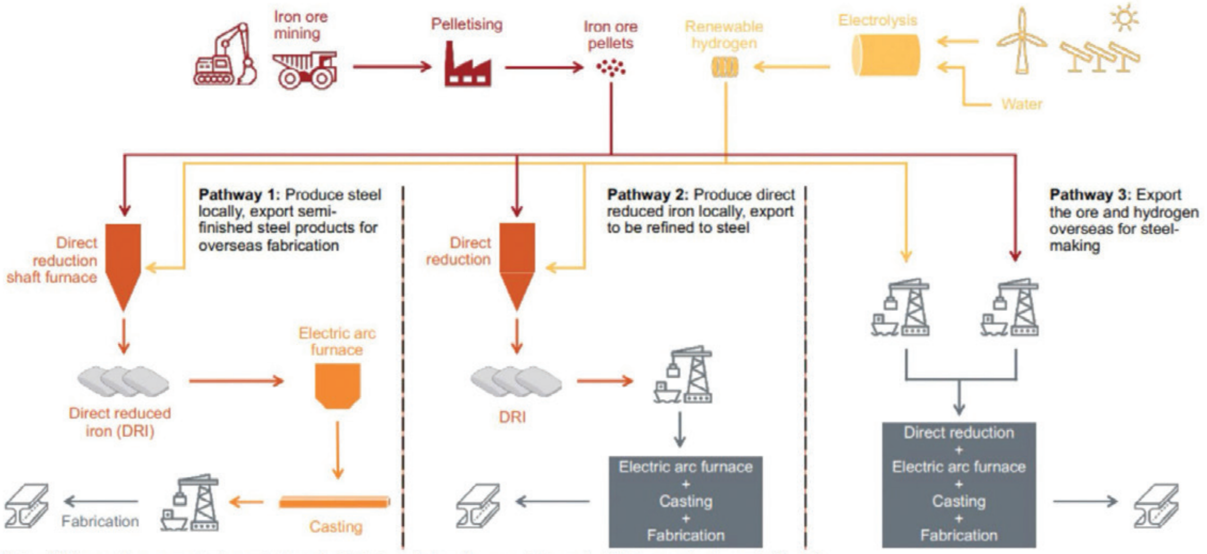
Clean steel projects with green hydrogen component



Source: LeadIT – Green Steel Tracker

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

Figure 2.3: Green steel export pathways



Notes: All three pathways require low-emissions electricity in each step. Iron ore mining and pelletising need not occur in Australia.

Source: Grattan analysis. Some icons sourced from flaticon.com (2020).

Green steel export pathways (grattan.edu.au)

COMMERCIALISATION TIMELINE

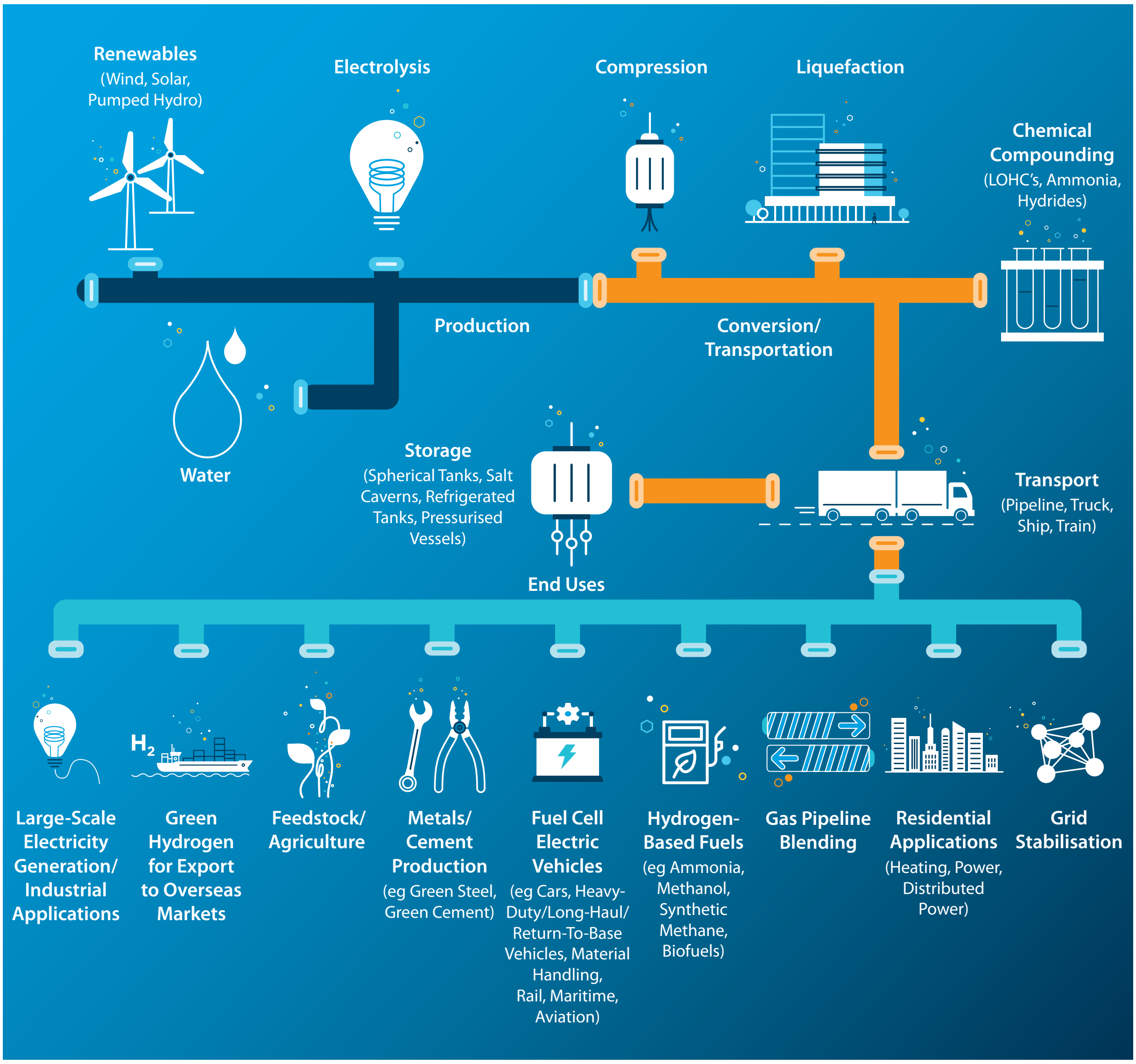
There are two clear pre-requisites for the commencement of commercial green steel - renewable electricity and commercial clean hydrogen.

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

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

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

THE GREEN HYDROGEN VALUE CHAIN



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