THE ANZ HYDROGEN HANDBOOK VOL II

HYDROGEN TRANSPORTATION

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

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

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

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

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

CONVERSION

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

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

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

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

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

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

COMPRESSION

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

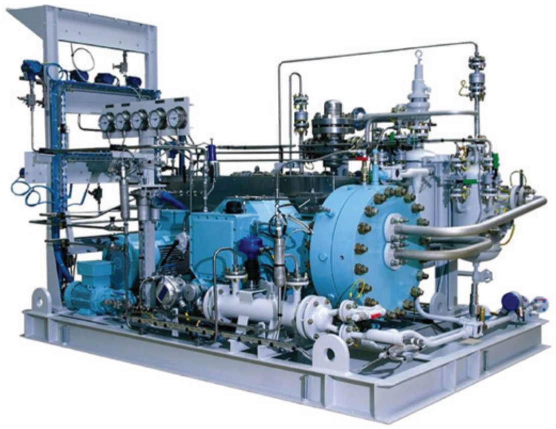
Hydrogen in its gaseous state is at an atmospheric level of ~1 bar, with compressed H_2 between 350-750 bar. Applying to what is required in various transportation methods, a pressure of around 70 bar is needed in transmission pipelines, and 1000 bar in storage tanks.[246]

Compression can be achieved in three ways:

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

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

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



Hydrogen compressor machine (neuman-esser.de)

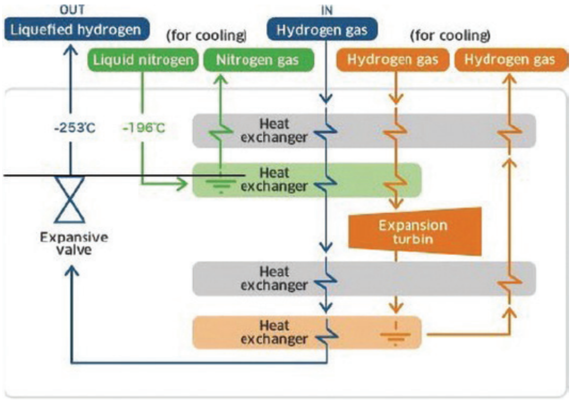
Electrochemical compressors can also be used via PEM technology to drive the dissociation of H_2 at the anode, and its recombination at higher pressures at the cathode.

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

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

LIQUEFACTION

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



The hydrogen liquefaction procedure (global.kawasaki.com)

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

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

Linde's hydrogen liquefaction plant (fuelcellworks.com)

LOHCS

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

Perhydro-dibenzyltoluene (PDBT) and methylcyclohexane (MCH) are the most well investigated LOHCs.[251] PDBT has a volumetric hydrogen storage density of 57kg/m$_3$, and MCH has 47kg/m$_3$.

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

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

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

AMMONIA

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

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

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

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

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

TRANSPORTATION

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

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

Cost of transportation methods

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

PIPELINE

Hydrogen can be transported in pipelines in two ways:

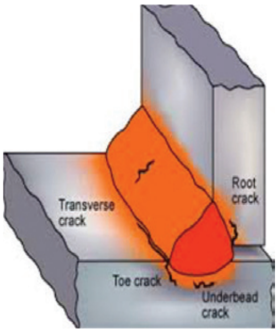
1. Blended into existing natural gas pipelines.
2. Building new specialised H_2 pipelines.

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

Blending into Existing Gas Network

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

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



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

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

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

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

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

New Hydrogen Pipelines

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

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

Costs

Overall, the levelised cost of transporting H_2 via pipeline over a distance of 50km is around A$0.1-0.3/kgH$_2$. It is estimated that this cost could also fall as low as A$0.06-0.2/kgH$_2$ if HDPE pipe is used and storage costs reach their lowest potential. The upper end of this price scale arises from the need for and operational costs of injection stations on the transmission and distribution grids to maintain pressure.

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

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

TRUCKS

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

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

Truck with a compressed hydrogen tube trailer

Truck with a liquid hydrogen trailer

CGH_2 vs LH_2 trailer types (energy.gov)

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

For CGH_2, a single trailer can only hold up to 1,100kgH$_2$ (at 500 bar) in lightweight composite cylinders giving it the lowest H_2 carrying capacity of all trailer technologies. Even this weight is rarely achieved in practice due to safety regulations limiting the allowable pressure/ dimension/ weight of the tubes.

LH_2 cryogenic tanker trucks can carry up to 4000kgH$_2$ and are commonly used today for journeys of up to 4000km. They are unsuitable for any greater distances as the H_2 heats up and causes a rise in pressure, and are comparatively quite expensive due to the energy intensity required to maintain the highly-insulated vehicle.

Costs

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

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

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

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

Cost comparisons across trailer types

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

SHIPS

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

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

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

Other H_2 pilot ship projects underway include:

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

The Suiso Frontier (hydrogenenergysupplychain.com)

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

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

Costs

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

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

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

OTHER

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

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