Welcome to the wonderful world of hydrogen

Key points

- Hydrogen has become a clean energy buzzword. The technologies and the nature of the energy vector it proposes to create appears to be thinly understood by many who extol its virtues. There is growing interest, investment and funding to accelerate development of hydrogen-related technologies. There is also a growing list of claims, proposed hydrogen projects and hydrogen-linked investments that should be regarded with caution.
- Hydrogen is potentially the most promising natural complement to intermittent renewable energy, by using times of surplus renewable electricity to create green hydrogen (a fuel). The stored hydrogen would then be used to provide energy when renewable electricity is scarce, and possibly replace fossil fuels used in specific industrial applications like steel. Maybe hydrogen can do some or even all of these jobs, but hydrogen is not yet a cost-effective solution.
- Detailed information on the proven costs of different parts of the hydrogen supply chain are varied. Many technologies are infant, unproven and theoretical. There are almost no commercial applications or scale of production of green hydrogen (from renewables) in the world.
- Hydrogen is not a single technology. It involves a supply chain made up of four separate processes: production, use, storage and transport. Each is challenging. Some more than others. Potential costs and complexities in processes like storage appear to have been largely overlooked, yet information emerging suggests they could pose significant efficiency and technical challenges at scale.
- It is possible to co-fire hydrogen in gas power stations but it will produce expensive electricity.
- Independent reviews of the cost of producing and storing hydrogen vary widely. There is wide diversity in what is considered the most efficient technique for storage: low pressure tanks, cryogenics or underground salt caverns? The cost of compression is sometimes completely overlooked. Moving hydrogen is also challenging.
- Research into hydrogen technologies is important and should continue. It would be prudent to take a considered perspective of the technology and plan accordingly.

Introduction

Over the past three years, hydrogen has become an energy buzzword. It is proffered as the solution to critical technical challenges in the decarbonisation of energy systems and industrial processes. This paper will consider the potential roles for hydrogen in the 21st century, its competitors and complements, what it can do and what it can't do and the main challenges in delivering these solutions.

The basics

Hydrogen is the smallest, lightest, least dense and most abundant element in the universe. It is the antipode of most conventional resources: ubiquitous yet difficult to manage and contain. It exists as part of some of the most common materials and products: in water, sugars, oil and gas, coal, timber and plastics. Isolated as hydrogen gas, it featured prominently in many 20th century industrial and energy systems yet is now being re-purposed and re-cast to solve new 21st century energy challenges.

Unlike most other resources, hydrogen is not scarce or geographically constrained. Everyone has access to the raw materials, and anyone can make it. There are some caveats on this: access to abundant, low-cost renewables are likely to be an advantage in lowering production costs. Access to large scale storage (like specific salt caverns in certain parts of the world) may also be an advantage. The challenge with hydrogen is not scarcity and extraction, it is in the transformations: from water to hydrogen, hydrogen to power station or to storage, and transforming hydrogen so it can be moved safely and cost-effectively to where it's needed. Handling hydrogen is not easy. Research into hydrogen is all about how to isolate it, compress it, store it, use it and move it.

Hydrogen forms as a gas H2 at room temperature and liquefies at -253℃ just above "absolute zero" (-273℃) which is the lowest temperature possible in the universe. This is extreme. It is much less dense than air (0.09 kg/m3 compared to 1.13 kg/m3), and, as a result, getting hydrogen gas into a compressed, let alone a liquid state, to store, ship or move it, requires enormous amounts of energy. By comparison, natural gas can be liquefied at -160℃ for shipping overseas.

The attraction of hydrogen as a fuel is it has formidable energy density by weight: three times more energy per kilogram than petrol, but conversely it has a third as much energy per *litre*. Cost effectively storing pure hydrogen is technically challenging and energy intensive. This is important, because the primary role of hydrogen in a zero-emissions energy system is as a form of energy storage.

Zero emissions hydrogen "fuel" can be made by running zero emissions electricity through water, capturing and storing the hydrogen. This process is relatively simple to demonstrate. It simply requires a 9-volt battery, a paper clip and a glass of water. The challenge with industrial green hydrogen is to make the extraction and subsequent storage processes cost effective at scale.

Hydrogen burns differently to methane (natural gas), providing an immediate release of energy, like an explosion, which poses safety and engineering challenges, particularly when using high concentrations of hydrogen. Some engineers believe this makes it difficult to use hydrogen above around 25 per cent blend with methane without changing the equipment it will be combusted in (power station turbines, cookers etc). Hydrogen is highly sensitive to any sort of spark and will combust almost immediately.

Hydrogen is also about three times less energy-dense than methane. That means that as the ratio of hydrogen rises, the volume of energy being delivered through the same pipelines decreases. Prolonged hydrogen contact with metals makes them brittle. This is likely to require new operating equipment if hydrogen is used at high concentrations.

Hydrogen in the 20th century

Hydrogen was used to perform five important/notorious tasks in the 20th century:

As the main fuel in town gas (reticulated gas that preceded natural gas), as a lifting gas used in airships (most famously the Hindenburg), as the primary source of fuel in rocket science (including the Apollo program), extracting sulphur and hydrocracking low grade hydrocarbons in the oil industry and in industrial ammonia production used to make fertilisers.

The nature of these hydrogen production processes is insightful: town gas was made by heating coal without oxygen and the mixture of hydrogen, carbon monoxide and methane was pumped directly into the gas reticulation system (the presence of carbon monoxide resulted in accidental poisoning and suicides). Hydrogen for airships was produced by a range of chemical processes and the gas was injected directly into the airship. Hydrogen used in making ammonia is reformed from natural gas via steam reforming and then injected direct into the ammonia production process (known as the Haber-Bosch process). The first liquid hydrogen production for US space exploration was expensive. The liquid hydrogen cost around USD$30/kg.

The common feature of 20th century industrial and commercial hydrogen was that it was made and used simultaneously. The only exception in the highly specialised (and expensive) applications used in rocket science where hydrogen was stored in cryogenic tanks for use as rocket fuel.

20th century hydrogen was a derivative of fossil fuels: it was produced by reforming hydrocarbons, typically natural gas. This process produced carbon dioxide (greenhouse gas) as a by-product. The 21st century hydrogen challenge is to produce low-cost hydrogen at scale without these emissions.

Substituting fossil fuels with green hydrogen poses four basic technical challenges: reducing the cost of making green hydrogen, adapting technologies and processes to replace carbon-based fuels that use hydrogen (power stations, steel mills), improving the efficiency and reducing the cost of storing hydrogen and cost-effectively transporting hydrogen.

Hydrogen: Make. Use. Store. Transport.

Making hydrogen

There are three basic ways of making hydrogen, denoted by three colours:

Grey hydrogen: produced from reforming fossil fuels like oil and gas, accounting for 98 per cent of current global hydrogen production, but the process produces significant greenhouse emissions.

Blue hydrogen: where hydrogen is split from methane (natural gas) using steam methane reforming, and the carbon dioxide produced is captured and sequestered. This requires access to cost effective carbon sequestration, which remains challenging.

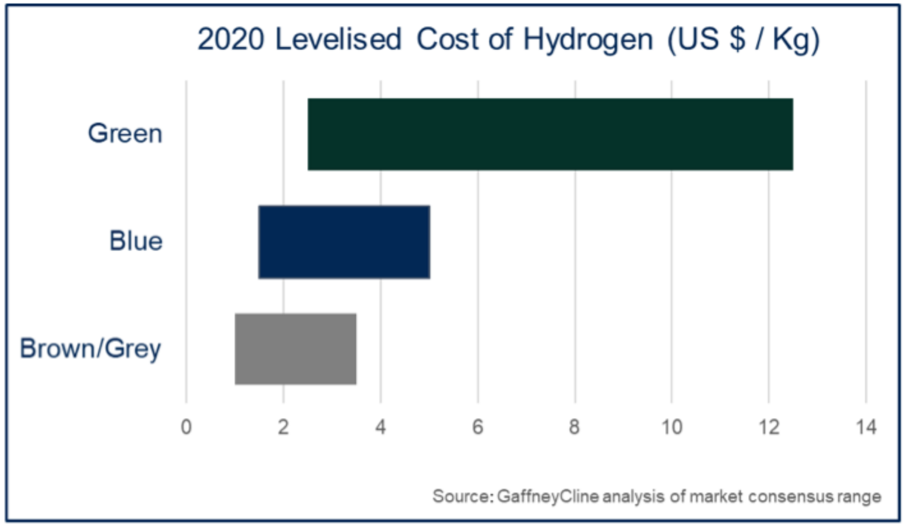
Green hydrogen: is hydrogen made from the electrolysis of water, powered by clean energy sources. It is technically possible to make green hydrogen today, but the cost remains commercially prohibitive. Most research is focussed on reducing this cost to a target cost of around $2/kg.

The clean technology focus is on development of blue and green hydrogen technologies.

- Blue hydrogen

Oil and gas companies like Shell and Woodside are unsurprisingly keen to develop blue hydrogen technologies and utilise their own expertise and existing hydrocarbon resources. The cost of hydrogen produced by steam methane reforming is claimed to be as low as around USD$1/kg, assuming the cost of the methane feedstock is in the order of $5/GJ, but the cost of sequestration is in addition to this, and only where it is geologically available.

Figure 1: Levelized cost of hydrogen, $USD/kg 2020,



Source: Gaffney Cline

Blue hydrogen is seen by some as a short to medium solution while green hydrogen costs remain uncompetitive. Sequestration is a proven but expensive technology that consumes large amounts of energy in the extraction, compression and pumping of the carbon dioxide.

Some blue hydrogen developers are already broadening their efforts to development of green hydrogen technologies. Blue hydrogen production is only around 0.6 million tonnes a year, compared to 76.5 mt/year of grey hydrogen, while green hydrogen supplies only 0.2 million tonnes a year.

Analysts Gaffney Cline estimate the current cost of grey hydrogen (in the absence of a price on carbon) is around USD$1-2.50/kg, compared to USD$3-4/kg for blue hydrogen and USD$4-12/kg for green hydrogen.

- Green hydrogen

The desirability of green hydrogen is twofold. First, the production of green hydrogen (clean electricity electrolysis of water) does not produce any emissions, just hydrogen and oxygen. Second, the green hydrogen electrolysis/production process is a natural complement to large scale intermittent renewable generation. Green hydrogen electrolysis can covert renewable electricity into hydrogen at times when there is an over-supply of renewable generation from wind and solar generators. This hydrogen could then be stored and used later as a source of dispatchable clean electricity when intermittent renewable generation is insufficient to meet demand.

There are currently four types of electrolyser used currently under investigation in green hydrogen technology development:

- Alkaline electrolysers – mature technology, uses an electrolyte solution
- Polymer electrolyte membranes (PEM) – commercial scale, uses membranes, high pressure, most advanced currently available
- Anion Exchange Membrane (AEM) – lab scale, could be more efficient than PEM
- Solid oxide electrolysers (SOEC) – lab scale, very high temperature, could be more efficient than PEM

The technologies have different cost and efficiency advantages in converting electricity to hydrogen, capturing the hydrogen and in the cost of building and operating the plant. These are some of the critical factors in reducing the final cost of green hydrogen production.

In total there are four critical factors that determine the production cost of green hydrogen:

The capital cost of the electrolysis technology (measured in $ per KW of capacity) – currently between $714 and $2571/kW.

The cost of green electricity (measured in $ per KWh). A dedicated renewables facility could deliver electricity in for around $0.041 to $0.06/kWh. One opportunity frequently cited is for electrolysers to connect to a grid such as the NEM and to run only when the electricity is very cheap or even negatively priced. This will affect its capacity factor (see below).

The conversion efficiency of electrolysis (measured in kWhs needed to make 1 kg of H2 or as a percentage of the maximum heating value of hydrogen which is 142 MJ/kg which is equal to 39.4 kWh/kg). The IEA estimate a conversion efficiency of around 62 kWh/kg or 64 per cent.

The capacity factor (measured as a percentage of time the electrolysis equipment is operating) – depends on the renewables sourced. A standalone project based on either wind or solar would typically have a 20 to 40 per cent capacity factor, depending on the quality of resource. Most such projects, at least in Australia, are targeting combined wind/solar installations, so are likely to be targeting higher utilisation. A grid connected electrolyser could get electricity 24/7, but it could be hard to establish its “green” bona fides, and would end up paying the average wholesale price. If it was targeting low and negative prices, it would run at a lower capacity factor, dictated by the level of price volatility in the market. For example in the final quarter of 2020, South Australia’s spot price was negative 17 per cent of the time, while in NSW negative spot prices were very rare.

The subject of the actual versus potential costs of hydrogen production is hotly discussed at the moment. The Australian Renewable Energy Agency has estimated the potential cost of hydrogen was AUD $ 18.70/kg, falling to AUD $11.30/kg if batteries were integrated in the process.

Analysis prepared for the International Council on Clean Transportation estimated the current and future cost of hydrogen production ranged from between USD \$6.62/kg and USD \$21.76/kg now and USD \$4.90/kg to USD \$12.46/kg by 2050.

Understanding the cost of hydrogen

An indicative cost stack of a hydrogen electrolyser breaks down as follows:

If:

- 1 kg of hydrogen produces around 130MJ of energy
- 7.69 kg of hydrogen are needed to make 1 GJ of energy
- 62 kWh of green electricity needed to make 1 kg of hydrogen
- 477 kWh of green electricity is needed to make 1 GJ of energy
- The cost of 1 kWh of green electricity is \$0.05
- Then the energy cost of 1 kg of hydrogen is around \$3.10 and the energy cost per GJ is around \$24 per GJ of energy.
- In addition, 1kg hydrogen requires 9 litres of water.
- The capital cost of electrolysis is around \$1200 per kW.

At a capacity factor of 40 per cent each kW of electrolyser capacity produces around 62 kg of hydrogen each year. A rough amortised cost of this capital would be between \$2-\$3 per kg of hydrogen

The total production cost of each kilogram of hydrogen in this scenario would be around \$5-\$6/kg.

The International Renewable Energy Agency (IRENA) produced a report in 2020 suggesting the cost to make green hydrogen could be between USD\$3 and \$6/kg right now but these costs could fall further. The International Energy Agency has also assessed the costs for production of green hydrogen.

Scale up

While there is growing output and increased funding for development of green hydrogen, there remains a wide range in the forecasting of future costs and time frames for commercialisation of different technologies. This scale of uncertainty is consistent with immature technologies.

The scale of global hydrogen electrolysis and production growth is currently only a few megawatts of capacity each year, but the IEA are predicting global electrolysis capacity could be increasing by 1500MW a year by 2023, and global demand for blue/green hydrogen could reach 8 million tonnes a year by 2030. In 2019 the Australian Renewable Energy Agency announced a \$70 million Renewable Hydrogen Development Funding Round with seven (mostly 10MW electrolyser) projects shortlisted and the successful projects announced in 2021.

The largest electrolyser in the world was commissioned in January in Canada by Air Liquide. The 20MW PEM electrolyser will run continuously using hydroelectricity to produce green hydrogen. The choice of hydro to power the facility is to reduce cost and increase output, but is not a practical example of how hydrogen would complement intermittent renewables.

The largest in Australia is currently a 1.25MW PEM electrolyser built by Siemens and installed by the Australian Gas Infrastructure Group (AGIG) in the Hydrogen Park in Adelaide. It is a high-cost, demonstration project to blend 5 per cent of hydrogen gas into the local natural gas network.

Using hydrogen

Hydrogen combusts at a similar temperature to methane (natural gas), but only produces water as a by-product. Hydrogen can therefore be used as a substitute for gas in industrial applications like electricity generation, high temperature kilns (cement, brick), industrial ovens and other high temperature applications. It may also be able to replace coking coal as the reductant in steel making. The technologies required to utilise hydrogen in these applications are still immature.

Electricity generation

A small but growing number of energy utilities, governments and entrepreneurs have been proposing incorporating blue hydrogen as a fuel into new or existing gas power stations. These include:

- In 2018 Swedish government owned utility Vattenfall proposed to convert one of the three 440MW combined cycle gas turbines at its Magnum power station in the Netherlands by 2023. Mitsubishi Hitachi Power systems would provide the turbine conversion technology.

- A "letter of intent" has been signed by Vattenfall, Mitsubishi, Shell and the Port of Hamburg to build a 100MW electrolyser on a former coal fired power station site.
- ENGIE and INEOS Phenol are looking to develop a commercial scale gas-hydrogen cogeneration plant (using 10 per cent blend of hydrogen) in Doel, Belgium.
- Plug Power has plans to build a 125MW electrolyser to co-power a 450MW gas power station in New York state.
- US energy company Black and Veatch claim to be retrofitting a 485MW CCGT gas power station at Long Ridge in Ohio to run on a gas-hydrogen blend by the end of 2021.
- Mitsubishi Hitachi Power Systems will build hybrid gas-hydrogen turbines for the Intermountain Power Project in Utah, with plans to be on-line by 2025.
- Danskammer Energy is proposing to upgrade an existing New York State power station into a 535 gas and hydrogen hybrid.
- In Australia resources company Fortescue has raised the possibility of building a gas-hydrogen turbine at Port Kembla.
- The South Australian Labor opposition has announced a "Hydrogen Jobs Plan" which includes 250MW of hydrogen electrolysers to fuel a 200MW hydrogen power station, supported by 3600 tonnes of liquefied hydrogen storage (there is no consideration of the need to build a hydrogen liquefier in the plan).

While hydrogen generation projects have been proposed since 2018, they have so far tended to stall between announcement and delivery. This may be due to commercial and technical differences between announcing hydrogen projects and delivering them.

Hydrogen fuel burns with a higher flame temperature than methane, increasing emissions of poisonous nitrous oxide (NOx) emissions. It releases energy more suddenly (explosively) and will ignite with almost any spark. Hydrogen is corrosive when it is put in prolonged exposure to metals.

Solutions to these technical challenges are being explored by world leading industrial technology development companies like Siemens, GE, Wartsila and Mitsubishi. They are competing to deliver world leading hydrogen technology to governments and energy companies, although their public comments on the cost and readiness of hydrogen generation vary significantly.

According to the European Turbine Network, no commercial scale turbine currently exists that can burn pure hydrogen. Siemens CEO Christian Bruch believes hydrogen will not be commercially viable before 2025 at the earliest, possibly not even until the next decade.

While Wartsila Energy is exploring how to build pure hydrogen power stations, they argue you cannot use conventional gas power turbine technology with more than 25 per cent hydrogen. GE claims it has been successfully blending more than 70 per cent hydrogen into a gas turbine in Spain and claims hydrogen is market ready.

Green steel

The production of steel from iron ore currently requires coking coal as a key ingredient: it acts as a reducing agent (removes the oxygen from iron ore or iron oxide), as a source of carbon for the final steel product (steel is an alloy of iron and carbon) and to provide heat for these processes. The combustion of coal in blast furnaces is a major source of greenhouse emissions. Hydrogen can replace two of these three roles: as a reductant and to provide heat.

The process of replacing coal with hydrogen is under early development in Europe. A Swedish steel and energy conglomerate H2 Green Steel has announced plans to develop a pilot hydrogen fuelled steel milling in northern Sweden, using hydroelectricity to produce the hydrogen, with production scheduled to commence in 2024. Germany's largest steelmaker Thyssenkrupp has announced plans to build its first hydrogen fuelled pilot steel mill in Duisberg by 2025. As with electricity production, lowering the cost of green hydrogen production will be critical to the commercial viability of green steel.

Hydrogen for other industrial uses

The potential application of hydrogen in other industries is less developed than for energy and steel. Cement manufacture, like steel, produces greenhouse emissions both in the chemical reaction to make clinker – where limestone is converted to lime producing carbon dioxide. It also produces emissions from the use of fossil fuels to heat its kilns. Cement companies are exploring the feasibility of using hydrogen as a partial substitute for gas in firing cement kilns. Current thinking is that new chemistry for the cement making process will be required to fully decarbonise cement production.

Dutch food company AMF has claimed to have developed the world's first hydrogen fuelled tunnel oven for industrial food manufacture.

Storing hydrogen

While there has been significant attention paid to the methods and cost of producing zero emissions hydrogen, there has been less discussion around cost effective methods of storing it. Storage of hydrogen is critical given it will be needed to fuel dispatchable electricity generators and large industrial processes that will need to operate continuously.

Hydrogen requires significant amounts of energy to compress and its small size makes it capable of escaping more easily through containers than many other substances. The very cold temperatures needed to keep in liquified can make containment metals brittle. It requires special engineering to compress and hold hydrogen at scale.

The National Hydrogen Roadmap identifies three different types of hydrogen storage:

Compression: low pressure tanks, pressurised tanks, underground storage and line packing in gas pipelines.

Liquefaction: Cryogenic tanks and cryo-compressed.

Material based: converting hydrogen to other materials, such as ammonia.

The roadmap claims storage is expected to add $0.3/kg to the cost of hydrogen, with liquefaction adding an additional $1.59-$1.94/kg and ammonia synthesis adding $1.10 to $1.31/kg. these more expensive types remain under consideration because they may facilitate transport of hydrogen (see below).

There does not yet appear a global consensus on the most efficient and cost-effective hydrogen storage methods. The US Energy Storage Association observes that small amounts of hydrogen (a few MWh) can be stored in pressurised tanks, while they think the best option for much larger volumes is in large underground salt caverns pressures of around 2900 PSI (200 BAR).

Potential locations for such salt caverns in Australia are mostly located in remote regions like the Pilbara and south western Queensland. No exploration licences have yet been issued to develop them, lets alone exploratory work done on the cot and feasibility of such facilities. European researchers have identified up to 85 PWh worth of hydrogen storage in salt caverns. The HyStorIES project has been funded by the EU to explore hydrogen storage beyond salt caverns because of the geographical and economic constraints this imposes.

The South Australian opposition has announced its plans to store 3,600 tonnes of liquefied hydrogen in tanks costed at only $31 million. The biggest cost in storing liquefied hydrogen is likely to be in the liquefaction process itself: according to the US Department of Energy a 200 tonnes/day hydrogen liquefier would cost around USD$500 million – more than the hydrogen storage tanks or the electrolyser.

At achievable, cost-effective storage densities of 100 bar in aboveground vessels at 20 degrees Celsius, the density of hydrogen is 7.8kg/m3. This low density requires large volumes of storage tanks. So the storage per tank is cheaper, but the number will need to be greater, which will increase costs. All methods to store hydrogen will require some sort of compression, and this will require some input of energy. The more compression, the more energy, the more cost.

Despite the accelerating list of hydrogen fueled electricity generation, technical research on hydrogen storage is less developed. Hydrogen storage requires the removal of residual oxygen, drying and compression, yet there is little technical information available on the steps of hydrogen conditioning.

It is also possible to store hydrogen in fuel cells, which were pioneered to power the command modules in the Apollo program. Fuel cells work like a rechargeable battery, charging and discharging electricity by converting water into hydrogen and oxygen (charging) and then releasing energy by recombining the hydrogen with oxygen.

Transporting hydrogen

Of all the four "tasks" of developing a hydrogen economy, the process of moving hydrogen at scale appears to be the most challenging. Moving a light, volatile and diffuse substance is theoretically possible, but poses a number of major physical obstacles.

Like other technical discussions, the debate around how to move hydrogen is immature. Proponents suggest transport of hydrogen by pipeline, by cryogenic storage or by converting hydrogen into other more easily movable substances including ammonia or radical new pastes.

Hydrogen can be transported in pipelines in the same way natural gas is currently moved. The Hyblend project by the US National Renewable Energy Laboratory (NREL) is exploring the technical challenges in blending hydrogen in natural gas pipelines.

Pipeline transmission of hydrogen is possible, but requires investment in specific infrastructure that uses polymers rather than steel, which are more resistant to the evasive nature of hydrogen atoms and their corrosive impacts on metals.

Cryogenic storage and transport is, to date, used mainly in rocket science where the high cost of storage is reflected in the high value of its use. The Hydrogen Energy Supply Chain (HESC) project in Victoria's Latrobe Valley is exploring liquefying and shipping hydrogen to Japan. The project will spend nearly $500 million to make and shift three tonnes of hydrogen. At $165,000 per kilogram, that's three times the value of gold.

Converting hydrogen into ammonia as a hydrogen carrier is being explored as a way of reducing the extreme physical properties of hydrogen. The cost of this is estimated in the National Hydrogen roadmap of $1.10-$1.33/kg. Lower liquefaction temperatures make it cheaper and easier to move ammonia thank hydrogen. Ammonia could then be used itself as a future fuel.

Overbuilding renewables

One idea to emerge in parallel to exploring hydrogen-based energy storage has been the idea has been to significantly overbuild renewable generation to reduce the need for higher cost storage solutions. This idea became popular in Europe around 2019. It appears to be anchored in theoretical modelling of how electricity grids work, as opposed to applied experience of high renewables integration.

In 2020 Wartsila claimed it modelled a scenario in which US electricity supply could be met by a major over-build of renewables, with solar capacity up to 4.3 times peak load in sunny regions requiring only 4 to 10 days of multi-day storage.

Domestic Policy

There has been a number of hydrogen related government announcements: a national hydrogen strategy was released in 2019. There is a South Australian hydrogen action plan and a Tasmanian Action Plan. Hydrogen is part of the NSW Government's Net Zero Plan, while Victoria has a Hydrogen Investment Plan. Queensland has a Hydrogen Taskforce and Western Australian has a Renewable Hydrogen Strategy and Roadmap. The CSIRO has produced a National Hydrogen Roadmap. The Australian Renewable Energy Agency has produced a report on the opportunities for Australia from hydrogen exports. The Grattan Institute has proposed that green hydrogen be used to revive the Australian steel industry.

Australia has signed a letter of intent to develop a Hydrogen Action Plan with Korea, a Joint Statement on Cooperation with Japan, has become a member of the US Centre for Hydrogen Safety and is working with Singapore and Germany.

In April 2021 the Morrison Government announced a further $539 million for "clean hydrogen" and CCS projects.

Summary

There is understandable global interest in the potential for hydrogen fuel technologies to provide a cost effective, clean energy storage solution and a new global energy vector. This enthusiasm appears at times to spill into hype and overconfidence about the performance and potential of the new technologies. Some individual proposed projects (like the South Australian hydrogen electrolyser) are larger than the entire current global installed capacity.

A sober review of the research into hydrogen technologies suggests genuine progress on hydrogen technologies is being made, but there is still a wide divergence between different claims around costs, timeframes and preferred technology pathways. These are all symptomatic of an immature technology development process. Convergence and clear pricing signals indicate a maturing market. Hydrogen does not appear to be anywhere near market-ready yet.

Further Reading

The National Hydrogen Roadmap, CSIRO

Australia's National Hydrogen Strategy, COAG Energy Council

South Australia's Hydrogen Action Plan

Victorian Hydrogen Investment Program

Queensland Hydrogen Taskforce

Tasmanian Renewable Hydrogen Action Plan

Western Australian Renewable Hydrogen Strategy and Roadmap

Opportunities for Australia from Hydrogen Exports, ARENA

Start with Steel: Grattan Institute