Materials, Resources and Sustainability series

Reading time: ~20 minutes

Hydrogen – opportunities and threats that demand good risk management

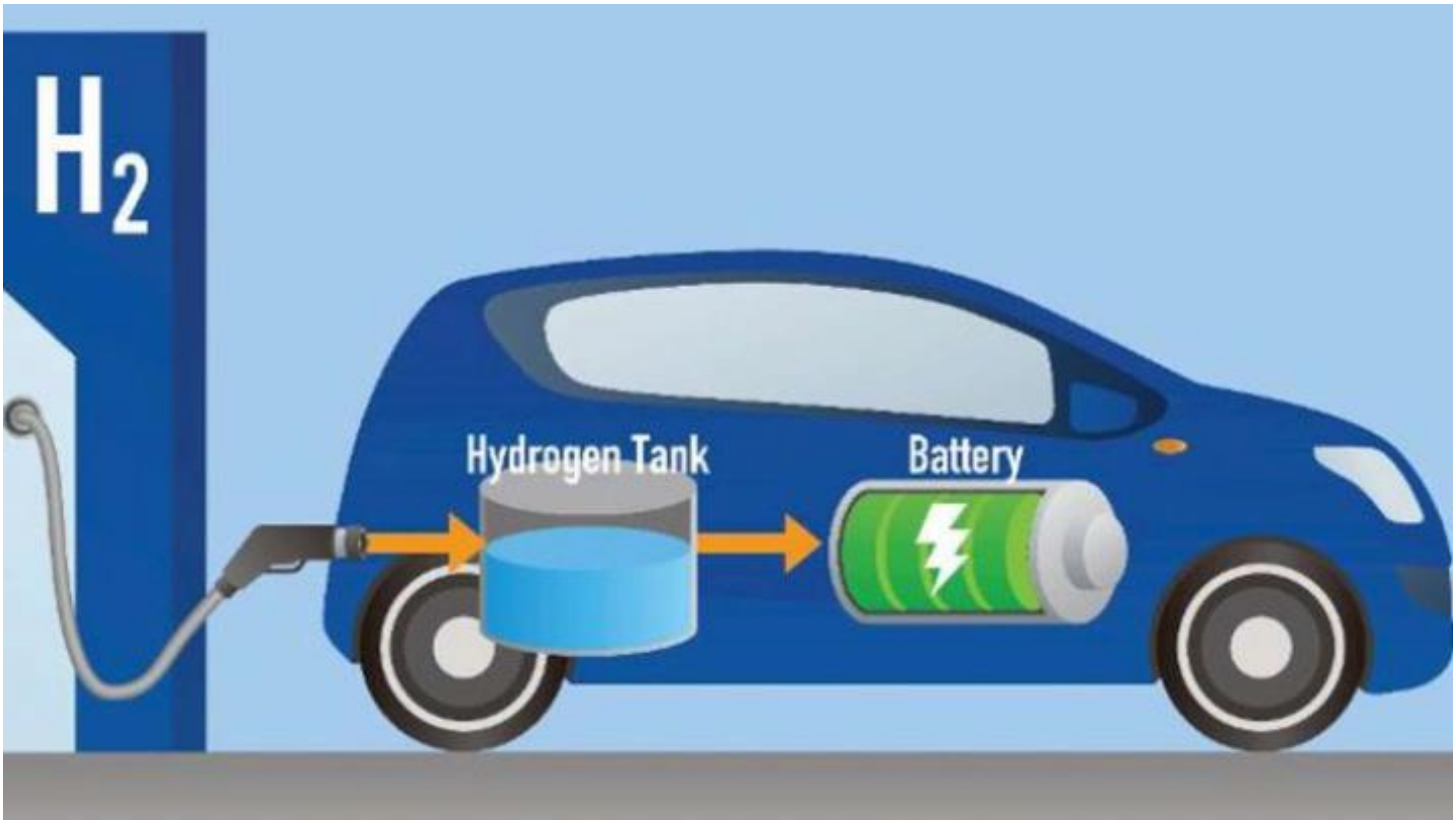


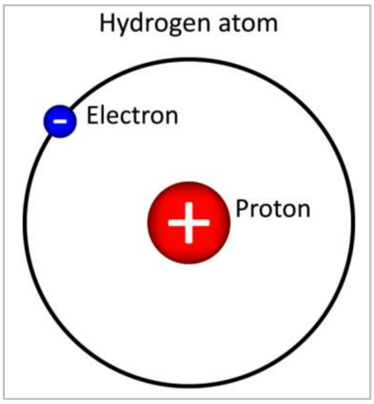
Image credit: QUT

Introduction

This paper is part of a series on **materials and resources**. In this series we ask how we can use risk management approaches, techniques and tools to improve the way we source, develop, use and dispose of the materials, resources and products that power our modern economy, and to support everyone involved in their value chains. The series uses [the United Nations Sustainable Development Goals] (the SDGs) as a common thread to discuss diverse sustainability and risk aspects and elements to each subject.

Hydrogen – the water-former…

Hydrogen is the simplest and lightest element in the periodic table, and the most abundant element in the universe. The electrically neutral hydrogen atom contains a single positively charged proton and a single negatively charged electron. The sun, in common with all stars, burns hydrogen furiously throughout its existence. Our moderately-sized star burns 600 million tons (that's 545 million tonnes) of it each second. At a smaller scale, hydrogen makes up about 10% of our body mass. [1]



In 1671, the Anglo-Irish natural philosopher, chemist, physicist, and inventor Robert Boyle discovered and described the reaction between iron filings and dilute acids, which results in the production of what we would later call hydrogen gas. Later, in the mid-1760's, the English scientist Henry Cavendish discovered that this gas was a discrete substance, and that it produces water when burned. In 1783 French scientist Antoine Lavoisier named the element hydrogen, deriving its name from the Greek *'hydro',* meaning water, and *'genes',* meaning forming – as hydrogen is one of the two *water-forming* elements (the other of course being oxygen).

You might assume that hydrogen is readily available on the Earth, but pure hydrogen gas is very scarce in Earth's atmosphere. Because it is much lighter than air, any hydrogen that enters the atmosphere rapidly escapes Earth's gravity. On our planet, hydrogen occurs mainly in combination with oxygen to make water, and in organic matter such as living plants, oil and coal (the latter two being in the form of hydrocarbons). Some algae and bacteria, using sunlight as their energy source, have been found to give off hydrogen under certain conditions.

As well as water, other compounds of which hydrogen is part of include methane (the simplest hydrocarbon, consisting of one carbon atom and four hydrogen atoms), alcohol, hydrogen sulphide, sulphuric acid and hydrogen fluoride.

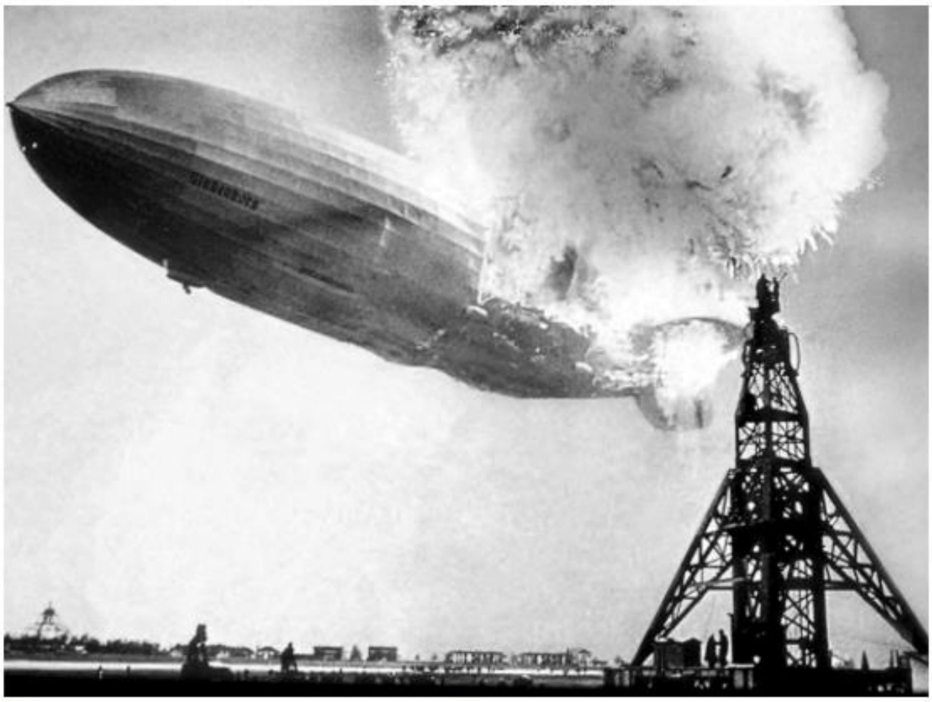
How long have we been capturing and using hydrogen?

We have been using hydrogen for energy-related purposes for a few hundred years. "Coal gas", which includes hydrogen, was used to power streetlamps in the UK in the 1800s. [2] The first fuel cell, a "gas battery" in which the formation of water from hydrogen and oxygen gas generated an electric current, was invented by the British physicist Sir William Robert Grove in 1839. [3]

Hydrogen is in the hydrocarbons that make up organic compounds such as oil, natural gas, methanol, and propane – which we use today for fuel. It can be separated from hydrocarbons through the application of heat – a process known as reforming.

Technically speaking, hydrogen is an *energy carrier* rather than a fuel. It is high in energy yield, and an engine that burns pure hydrogen produces almost no pollution. Similar to other forms of energy and fuel, great care must be taken in how it is stored and used, as it is highly volatile in certain conditions. Many decades ago, we saw examples of how dangerous it is, albeit as a lifting gas rather than a propellant.

In the early 1900's, as the aviation industry started to take off, we filled airships – those massive inflatable slow-flying machines – with hydrogen as a "lifting gas" (some airships were filled with helium). Unfortunately, due to the technology and materials available at the time, dozens of airship explosions occurred – including, memorably, the explosion of the Hindenburg in 1937 (which your author wrote a play about a long time ago). [4]



Hydrogen fire destroys Hindenburg, May 6, 1937

Winding the clock forward several decades, and moving from aviation and into space, NASA has used liquid hydrogen to power its spacecraft since the 1970s, including the huge Saturn V rockets that powered the Apollo missions to the moon (you can see one of them, on its side, at the Johnson Space Center Rocket Science Park in Houston). As NASA have described, the taming of liquid hydrogen – which included overcoming early technical failures – has proved to be one of their most significant technical accomplishments. Hydrogen is a light and extremely powerful rocket propellant – since it has the lowest molecular weight of any known substance and it burns with extreme intensity and force (at 3,030°C / 5,500°F). [5]

Move forward to today, and for the first launch of NASA's Space Launch System (SLS) rocket and Orion spacecraft that will send humans beyond low-Earth orbit, Exploration Ground Systems (EGS) at the Kennedy Space Center in Florida is working on the world's largest liquid hydrogen storage tank. [6] Other forms of fuel, such as liquid methane (remembering that methane contains hydrogen), are being trialled by space companies such as SpaceX.

Image: A liquid hydrogen storage tank is photographed at Launch Pad 39B on Nov. 8, 2019, at NASA's Kennedy Space Center in Florida. Credit: [NASA / Ben Smegelsky]

Perhaps the space industry can provide us with valuable learnings on how to harness and capture the potential for using hydrogen safely, to help us with our energy needs on Earth.

How are we currently using hydrogen around the world today?

According to the India & U.S. based market research and consulting company, Grand View Research, the hydrogen generation market size was valued at US$108.1 billion in 2016 and is predicted to grown at a healthy Compound Annual Growth Rate (CAGR) of 5.8% by 2025. [7]

Key to our present and future use of hydrogen is how we produce it. As explained by the World Energy Council and others, hydrogen can be produced through different processes. The energy source and the method of extraction defines whether it is considered as brown / grey, blue or green hydrogen. [8, 9]

- **Brown / Grey hydrogen** – 'Brown' hydrogen is manufactured via a Steam Methane Reforming (SMR) process from fossil fuels, or coal gasification. It currently accounts for almost all global production (with natural gas accounting for much of it). [64] These processes generate large amounts of CO_2 – the hydrogen is termed 'grey' if the CO_2 is released into the atmosphere. It is estimated that around 95% of all hydrogen manufactured worldwide is 'grey'. [9]
- **Blue hydrogen** – this is grey hydrogen, but with the carbon captured and stored (CCS). By using CCS, it is "somewhat greener" since CO_2 released into the atmosphere is greatly reduced, but it still generates carbon emissions. [64]
- **Green hydrogen** – this is the main focus for the future, because it is based on producing hydrogen using electrolysis and renewables and as a result to achieve zero CO_2 emissions in doing so. However, it is currently the most expensive.

According to the International Energy Agency (IEA), demand for hydrogen has grown steadily since 1975 and it continues to rise (see Chart 1). It is currently almost entirely supplied from fossil fuels, with 6% of global natural gas and 2% of global coal going to hydrogen production. Today, the production of hydrogen is responsible for generating around 830 million tonnes of CO_2 per annum. For comparison, this is equivalent to the CO_2 emissions of the United Kingdom and Indonesia combined. [10]

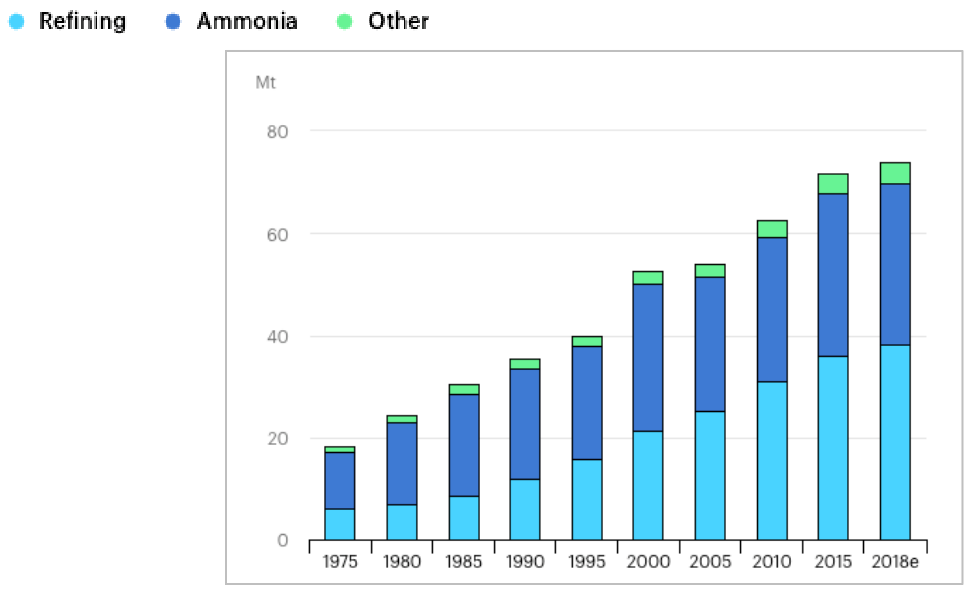


Chart 1: Hydrogen production volumes, 1975-2018. Image: The IEA, All Rights Reserved

The cost of hydrogen for energy – a key factor in its future adoption

Whilst recognising the current size of the hydrogen market, and positive growth projections for the future, it is important to consider that hydrogen currently accounts for a small percentage of overall global energy – about 4% of final energy use as of early 2020, according to the Financial Times. [47]

A commonly cited challenge with using hydrogen in our energy mix today, which is a factor impeding greater use, is its cost. From the manufacturing process through to the handling and transportation of the end product, it is comparatively expensive to produce and use compared to other energy solution options. [47] Green hydrogen in particular – which is a key area of focus for this paper – is still seen as expensive.

A report published in January 2020 by the Hydrogen Council titled Path to Hydrogen Competitiveness: A Cost Perspective, states that the cost of hydrogen solutions will fall sharply within the next decade. [48] Achieving cost efficiencies will be an important factor in determining its use in future.

The market for hydrogen around the world

Many countries around the world are developing plans to expand their use of hydrogen as an energy carrier. Today, Europe is a major market for hydrogen, with Asia-Pacific (including China) expected to be increasingly active in its production and use in the decade 2020-2030.

As described by the Canadian Hydrogen and Fuel Cell Association and the Hydrogen Council, today's hydrogen use can be categorised into five areas: [11]

1. Energy use by industry
2. Industry feedstock
3. Heat and power for buildings
4. Energy storage and power generation
5. Transportation

The first two areas are the main markets for hydrogen today. The hydrogen produced and used in these areas is mostly "grey" or "blue" hydrogen (which is not as environmentally-friendly as green hydrogen):

1. Energy use by industry

Various industries are already using hydrogen as a source of power. Industrial equipment, such as boilers and generators, is being modified to use hydrogen as a power source. In many cases, large industrial plants are using hydrogen in their energy mix as part of their strategy to reduce carbon emissions.

Image: Hydrogen and synthesis gas plant in Al Jubail, Saudi Arabia. Source: Linde

2. Industry feedstock

A feedstock is a raw material used to fuel machines and processes. For example, it is used in refineries, fertiliser production and the production of chemicals.
It is estimated that some 55 million tons of hydrogen are being used today as feedstock, mostly as "grey hydrogen".

Image: Hydrogen by dual feedstock plants. Source: Caloric

The next three areas are where hydrogen is being used in a smaller way, as of 2020.

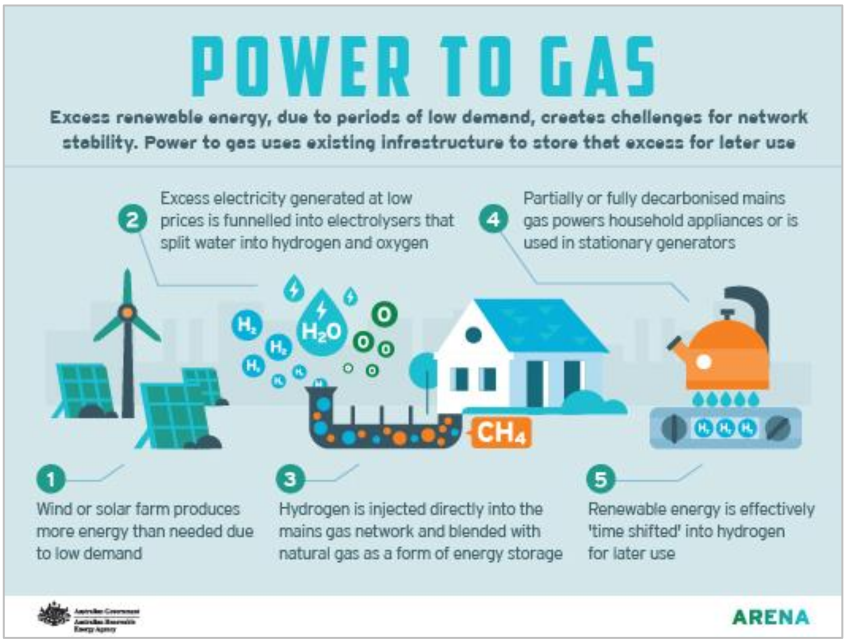
3. Heat and power for buildings

In places where existing gas pipelines exist, hydrogen is beginning to be blended with natural gas. Such “hydrogen blending” involves small amounts of hydrogen being injected into the natural gas grid. Hydrogen is also being converted into synthetic natural gas or used in dedicated hydrogen networks.

Source: [Arena]

4. Energy storage and power generation

Hydrogen is being used in various countries to store energy, for example, with power-to-gas facilities that convert power to hydrogen gas for storage.



For example, in Ontario, Canada, surplus electricity that is generated is used to produce “green” hydrogen gas, through Hydrogenics electrolysis technology. The hydrogen gas is stored and can be converted back into electricity when needed or blended with natural gas as a less carbon-intensive energy source. [12]

5. Transportation

Hydrogen fuel cells are being used, in a limited way so far, in vehicles and public transportation around the world today, including some cars, buses and lorries. Businesses in Canada and Australia, for example, are active in this space.

Image: Paul Kane / Getty images (The Guardian)

How could hydrogen play a part in our energy plans for the future?

There is a lot of discussion at the moment about the general future of all energy sources, in the wake of the impacts we have seen in 2020 due to the COVID-19 pandemic.

The Hydrogen Council believes that green hydrogen has enticing prospects for energy. Overall, the annual demand for hydrogen could increase tenfold by 2050 – from 8 exajoules (1 EJ = 10^{18} joules) in 2015 to almost 80 EJ in 2050. It is forecast that this would be enough to meet the world's current energy demand for two and a half months. [13]

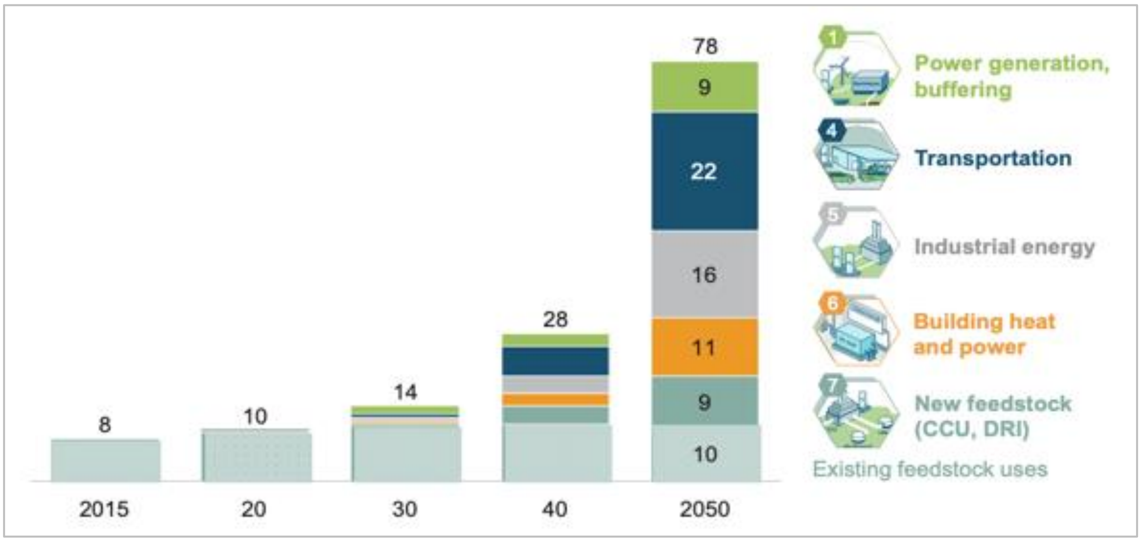


Image source: The Hydrogen Council, [Scaling up hydrogen]

The management consultancy, McKinsey, highlights the value of green hydrogen (and blue hydrogen) in a paper published in April 2020 about how the world can combat climate change. [61]

Whilst the projected possibilities for using green hydrogen look very positive, a key point to its ongoing adoption, as mentioned earlier, will be the ensure it is cost competitive compared to other energy solutions.

1. Energy use by industry in future

The Hydrogen Council believes that industrial use of hydrogen could be a major component of future green hydrogen use, second only to transportation. All manner of industrial equipment could be modified / built to use green hydrogen as a power source. Green hydrogen can be used as alternative to post- combustion carbon capture and storage. [14]

Buoyed by economic prospects, especially in Asia, hydrogen energy consumption by global industry is forecast to increase by 10% by 2050.

At the same time, international climate change agreements require CO_2 emission reductions of 30% in this sector: 2.5Gt (billion tons) less compared to today's levels, or 4.6Gt less compared to the reference scenario that the IEA predicts based on current trajectories. [14]

The Royal Society Report, Options for Producing low-carbon Hydrogen At Scale, provides a number of suggestions on how this could be achieved, including thermochemical, biological and electrolytic production options. [15]

Industry can reach this decarbonisation goal using three levers:

1. Improving energy efficiency by deploying best available technologies and production processes and recycling materials;
2. Switching from fossil fuels to bio-based fuels, renewable electricity, and/or hydrogen;
3. CCU (Carbon Capture & Utilisation) / CCS (Carbon Capture & Storage).

An example of opportunities with industry innovation and use of hydrogen concerns the steel-making industry. Research is being carried out into replacing coking coal which is used in the steel production process with hydrogen, as a way to reduce the industry's CO_2 emissions. Rather than produce liquid metal by heating iron ore and coking coal in blast furnaces, steel can be produced through a process called the Direct Reduced Iron (DRI) method, using hydrogen as a reductant. The World Steel Association says that the industry currently accounts for 7 to 9 per cent of all direct emissions from fossil fuels, a ratio that has remained roughly constant over the past decade. As an average, they report that for each tonne of steel produced there are 1.83 tonnes of CO_2 also produced. [55] It is hoped that this new production process using hydrogen in place of coking coal could make a big difference to the industry's carbon emissions. A key factor to its uptake will be to demonstrate that it is a cost-effective solution (more details are discussed later in this paper).

2. Industry feedstock in future

Current uses of hydrogen as industry feedstock could be fully decarbonised. In addition, hydrogen could be used to produce 30% of methanol and derivatives from captured carbon instead of methane, recycling more than 350 Mt of CO_2 into products. It could contribute towards low-cost ammonia production. It could also be used as an energy source to produce about 10% of the world's steel – roughly 200 Mt – using low-carbon direct reduction processes. [16]

3. Heat and power for buildings in future

From its very low base of today, the use of hydrogen for building heat and power could, it is suggested, grow to be some 10% of total future hydrogen use. [16]

New technological solutions are being developed and trialled. For example, a French consortium of the French Alternative Energies and Atomic Energy Commission and the start-up Sylfen has developed a hybrid energy storage and co-generation system for homes. [40]

The Smart Energy Hub can operate in electrolysis mode to store renewable energy as hydrogen, or in fuel cell mode to produce electricity and heat from previously produced hydrogen or methane.

Image: Panasonic residential fuel unit. Source: Bloomberg

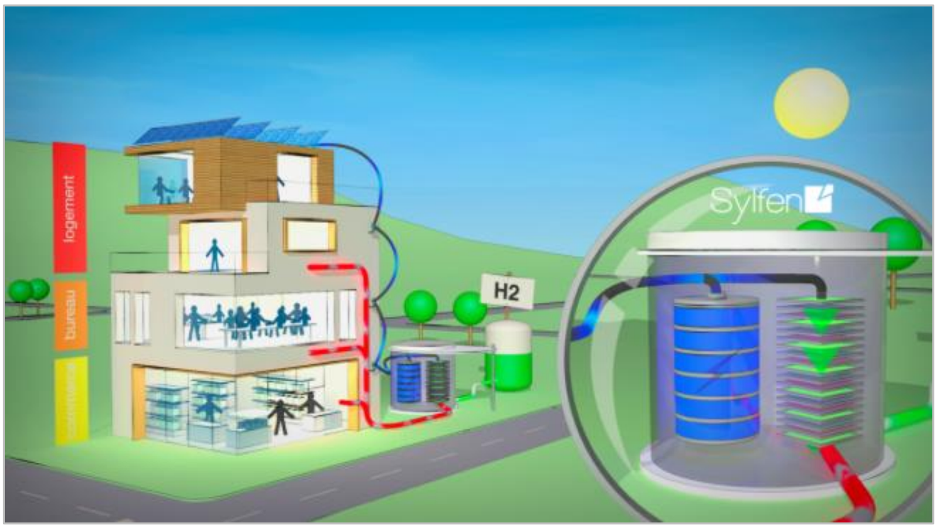


Image source: Sylfen

4. Energy storage and power generation in future

In the power generation sector, domestic or imported hydrogen could generate roughly 1,500 terawatt-hours (TWh) of electricity (a TWh is 1,000 gigawatt-hours). It could provide roughly 10% of the heat and power jointly required by the global household and industry sectors.
The share would likely be higher for residential heat and power in geographic regions with a high winter heating demand. Such regions tend to have a natural gas infrastructure on which hydrogen can piggyback (as described earlier). [16]

In addition to power generation, can energy storage offer an enticing prospect for how we use hydrogen? As the share of intermittent green energy sources rises, so will demand for energy storage to offset swings in supply. Hydrogen may offer an option for energy storage.

5. Transportation in future

This is a very interesting area, and a key one for the future of hydrogen fuel cell technology. It may be one of the faster-developing areas, and it may increase in use alongside battery-powered electric vehicles (EVs) – as long as it can be proven to be cost-competitive.

In early 2020, hydrogen-linked stocks reached their strongest values in more than a decade as investors started to bet that efforts to cut carbon emissions really will make hydrogen a viable alternative to fossil fuels for vehicles. [60]

Clean transport is a key part of moving to a low-emissions global economy. As car manufacturers phase out conventional petrol and diesel powered vehicles, both battery and hydrogen power options for EVs are being developed.

The Hydrogen Council believes that by 2050, hydrogen could power a global fleet of more than 400 million cars, 15 to 20 million trucks, and around 5 million buses, which constitute on average 20 to 25% of their respective transportation segments.

In automotive, hydrogen vehicles could range from roughly 10% for small cars and 20 to 25% for large cars and trucks to roughly 35% for vans. Hydrogen-powered trains could replace around 20% of the world's diesel trains. Hydrogen could also replace 5% of the world's fuel supply to airplanes and freight ships by 2050. [16]

Hydrogen-powered vehicle opportunities are therefore inclusive of large industrial vehicles, not only cars and buses.

A Canadian company, Loop Energy, has developed hydrogen fuel cell "range extenders" for short- and long-haul trucks. It is supporting the conversion of Nanjing's municipal bus fleet to hydrogen. [67]

Daimler announced in April 2020 that it will join forces with the Volvo Group to develop fuel cells for trucks, with the aim of bringing hydrogen-powered heavy-duty vehicles to the market in the second half of the decade. [59]

An Australian company, H2X, is aiming to produce a range of hybrid vehicles that primarily use hydrogen as the energy storage, including agriculture and other heavy vehicles, from a plant at Port Kembla, New South Wales, by 2025. [65, 66]

The mining company Anglo American announced in October 2019 a partnership with the energy services company ENGIE to develop and fuel the world's largest hydrogen-powered mine haul truck. Operational performance of the converted trucks is expected to be the same or better than the usual diesel trucks, with extra benefits of cleaner air, less noise and lower maintenance costs. [17]

In March 2020, the mining companies Anglo American, BHP and Fortescue, with engineering consultancy Hatch, confirmed that they are collaborating on a new Green Hydrogen Consortium, based in Western Australia, aiming to accelerate the production of renewable hydrogen. [62]

When it comes to cars, much has been achieved in recent years with battery-powered electric cars. Major manufacturers such as VW are making large investments in battery technology, and Tesla is globally known as a leading electric car manufacturer.

Hydrogen-powered cars, referred to as Fuel Cell Electric Vehicles (FCEV's) can play their part as well towards the greening of the car industry. They have distinct advantages, including their range and the time to refuel. As with larger vehicles, the safety of using hydrogen in cars must be proven. [18]

The Japanese vehicle manufacturers Toyota and Honda (which are examples of Japanese leadership in hydrogen technology) are advocates of hydrogen FCEVs. Toyota refers to hydrogen-powered vehicles as "essentially the next-generation electric vehicles". [19]

Image: A hydrogen fuel cell car, a Toyota Mirai, powered by a portable fuelling station. Source: Toyota

Audi (which is owned by VW) is also in this market, with their h-tron vehicle. [20] Their concept car is powered by a fuel cell which generates electricity from hydrogen. Audi says that it can produce hydrogen itself in its own power-to-gas plant using neutral, green electricity CO_2. With this idea, Audi is making an interesting proposal for the mobility of the future.

Will hydrogen filling stations replace good old petrol pumps? (image credit: Inside EVs)

A lack of hydrogen refuelling infrastructure is a key issue restricting hydrogen FCEVs today. While governments around the world are investing in electric charging infrastructure, and battery electric vehicles can also be charged from the home, investment in hydrogen fuelling infrastructure is inconsistent. [21]

However, with examples such as Hydrogen Mobility Europe (H2ME) – a project aimed at creating a pan-European network of hydrogen refuelling stations – taking shape, and with major players such as Shell investing in hydrogen, the future for this technology could be bright. [22]

As mentioned earlier, proving the safety of hydrogen for vehicle use is of paramount concern. In June 2019, an incident in Kjørbo, outside Oslo, Norway, led to two people being treated for minor injuries (caused by airbags being activated in their nearby car, which was not a FCEV) after a leak of hydrogen at the station ignited and created a pressure wave (there was no explosion at the station). [23]

And what about aviation and the potential to use hydrogen as an energy carrier, through hydrogen fuel cells? The aviation industry is said to be responsible for around 2% of all human-induced carbon emissions, and around 12% of transportation as a whole (compared to about 74% for road vehicles), although this is probably temporarily different in 2020 (due to COVID-19 and aviation restrictions).

Airbus is part of the Hydrogen Council and they state that they are looking into the technology. [39]

How can hydrogen itself be transported and distributed?

In order to make hydrogen cost-competitive to be shipped around the world, it needs to be shipped in liquid form. There are currently a number of technology options for shipping hydrogen globally. McKinsey Energy Insights provide an overview in the Hydrogen Council report on the "path to hydrogen competitiveness". [51]

The three major archetypes currently being considered are: [51]

1. liquid hydrogen (LH_2);
2. ammonia (NH_3), and;
3. a set of different technologies based on liquid organic hydrogen carriers (LOHCs).

Liquid hydrogen shipping costs, as of today, are high but it may turn out to be the most economic option, when hydrogen is the end use product.

Ammonia represents an enticing prospect for hydrogen transportation. As the Hydrogen Council advise, using ammonia as the hydrogen carrier has the benefit of leveraging existing infrastructure for global distribution. Also, the conversion from hydrogen to ammonia is a well-established technology. In cases where the end use is ammonia, shipping ammonia is the preferred option (but requires careful handling by certified operators due to its toxicity). When the end use is for pure hydrogen, a reconversion step is required, which is currently at an early stage of development. Also, reconversion requires access to low-cost clean energy at the arrival port in order to ensure a low-carbon or renewable hydrogen product. Depending on the technology evolution and local conditions, this reconversion step could add another US$1 to 2 per kg on top of conversion and shipping costs. [51]

Investigations into liquid organic hydrogen carriers are still at an early stage.

To attain low hydrogen costs at the point of use, the production of hydrogen, and/or its delivery to a major centralised facility such as a port, is part of the picture, but of critical importance also is the “last mile distribution” to the end user.

Central, large-scale uses like ammonia production (e.g. for fertiliser) or refining will usually produce hydrogen on-site or close to the production facilities. It may be distributed via pipelines. Such infrastructure at scale already exists today, and the cost contribution is a small part of the overall distribution cost, with limited cost-reduction potential.

For decentralised users of hydrogen, how it is delivered to them – the “last-mile distribution” mentioned above, is key. Today, this “last mile” can represent over 50 per cent of the total hydrogen cost to such users. According to the Hydrogen Council, if the industry can achieve growth and scale, with high levels of utilisation throughout the value chain, costs can and should be reduced. [51]

Three main options exist today for hydrogen distribution:
1. trucking of compressed hydrogen;
2. trucking of liquefied hydrogen, and;
3. pipelines.

The decision of which distribution option to pursue will differ from case to case, based on the demand profile and the distance from supply.

For short distribution distances, compressed gaseous hydrogen (GH_2) is currently seen to offer the lowest cost.

Liquid trucking is seen as being economical for distances above 300 to 400 km. If hydrogen is already available in liquid form at the production or delivery site, shorter distances are economical (refer to the points on the previous page about hydrogen transportation).

Building a new hydrogen distribution pipeline network is a significant investment over multiple years. It is claimed that it can become economical where large volumes are forecast. Another option is to use existing natural gas pipelines. Here, either hydrogen blending (as described earlier) or – if the network configuration allows for it – upgrades to pure hydrogen distribution, could be economic.

The Hydrogen Council believes that all options for hydrogen distribution should decline significantly in cost over the next decade to 2030 – possibly by about 60 per cent including production, and by as much as approximately 70 per cent when only considering distribution and retail. Cost improvements could bring the cost of hydrogen at the pump to less than US$5 per kg by 2030. [51] How this situation evolves will be likely be a key determinant to the overall use of hydrogen as part of our energy mix.

Looking at hydrogen with the SDGs

The production and use of hydrogen can be examined through the lenses of the SDGs. Looking at resource consumption and responsible use and disposal through the SDGs helps to give a balanced view of benefits and drawbacks, and challenges.

3. Good Health & Wellbeing

The fact that green hydrogen emissions are clean means that this energy carrier contributes towards good health and wellbeing. In cities, where pollution is being battled against, this is an important consideration.

7. Affordable and Clean Energy

A major draw card for investing in green hydrogen technology is the clean energy credentials it has. This has to be considered in conjunction with the cost of using hydrogen for energy, and its affordability. Challenges remain with reducing the costs to acceptable levels, comparative to other energy sources.

The impact of COVID-19 pandemic on energy production and use has led to many rapid changes, and many people suggest that green hydrogen can play a valuable role in the energy mix of the future.

Currently, grey and blue hydrogen production is more affordable, and infrastructure for it is in place. Investment is required in green hydrogen to make it scalable and cost-effective.

The International Renewable Energy Agency (IRENA) published a report in September 2019 exploring the potential for increasing the use of green hydrogen globally. The report notes that green hydrogen represents a "complementary solution that is especially relevant for countries with ambitious climate objectives." [24]
The Agency has said that 19 exajoules (an exajoule is one quintillion, or 10^{18}, joules) could be provided by clean hydrogen in 2050 – which could correspond to around 5% of global energy consumption. [44]

An example of including hydrogen in a nation's energy mix is the consortia of the Dutch transmission system operator Enexis, natural gas infrastructure company Gasunie and oil firm Nederlandse Aardolie Maatschappij BV (NAM). They announced in December 2019 that they are looking at an option of using excess solar power generation capacity in the north-eastern part of the Netherlands for hydrogen production. [43]

Enexis have said: "The research is examining the conditions under which it is feasible to directly convert locally generated sustainable energy into hydrogen," said the transmission system operator. "And whether that energy can be transported via existing gas pipelines to customers so that this green energy still contributes to the energy transition." [43]

This is encouraging for supporters of hydrogen, but a key factor will continue to be achieving the use of hydrogen as part of the energy mix in a cost-efficient way.

8. Decent Work & Economic Growth

Innovation and development in hydrogen is already leading to work opportunities and economic prospects in many parts of the world.

If the projected use of green hydrogen technologies grows as industry forecasters believe, it will help to generate a substantial amount of economic growth. [25]

9. Industry Innovation & Infrastructure

Research and investment is being pumped into the hydrogen industry around the world. Producing low-carbon green hydrogen in a cost-effective manner, and working out economic means for distribution and transportation, is key to enabling wide-scale hydrogen processing and system deployment.

Various initiatives are being pursued. [25] Some in the energy industry are focusing on investing in green hydrogen, whilst recognising that they will need to use grey and blue hydrogen to help build scale for green hydrogen in future. [26]

In Europe, the H2FUTURE project is aiming to show how to make green hydrogen technology cost-effective and sustainable. [27]

12. Responsible Consumption & Production

Many ideas about the consumption of hydrogen for energy have been included earlier in this paper.

An example of a new idea for responsible production was included in a report in early 2019 which suggested that North Sea gas producers, who have extracted oil from the North Sea for some 40 years, may in time be able to produce zero-carbon hydrogen by using electricity generated by offshore wind turbines to split the carbon molecules from natural gas. [28]

What is the position of different groups on hydrogen?

The general public

Many people may not have heard a great deal about hydrogen energy options, since much of the reported news for sustainable energy sources focuses on renewables such as wind, hydro and solar, plus battery power.

Our collective appreciation of the possibilities of hydrogen as an energy carrier may rise in the coming years, if more initiatives and examples of its use come to fruition and are reported on more widely.

Governments and international public policy

Some governments around the world are very proactive in pursuing strategies and policies involving hydrogen as part of their energy mix. Government actions are an important aspect of how hydrogen use will evolve in future. It is all the more important, given the recent dramatic changes in energy supply and costs, as the world deals with the COVID-19 pandemic.

Good policy-making can play an important part in its overall adoption and success. Governments should focus on ensuring an overall regulatory framework is sensible, which includes appropriate permitting rules to agree to hydrogen technology being used, and the right price for carbon. Careful and appropriate use and management of subsidies is an important part of policy control as well (for overall future energy needs, not just for hydrogen).

Some examples of the activities of a selection of governments around the world are as follows:

Japan

Japan is one of green hydrogen's most advanced markets at the moment. The Japanese lead the way in hydrogen fuel-cell vehicle development, with businesses such as Toyota and Honda (as mentioned earlier). Policymakers in Japan are keen to stimulate green hydrogen as an alternative to liquefied natural gas which the country is a big importer of. In September 2019 it announced a global action plan to set up 10,000 hydrogen vehicle refuelling stations over the next decade. [29]

Japan held the presidency of the G20 in 2019, and commissioned the International Energy Agency (IEA) to produce a detailed and comprehensive report on The Future of Hydrogen, which was published in June 2019. [30]

Australia and New Zealand

The Australian and New Zealand governments are active with research into hydrogen use. The Australian government COAG Energy Council has issued a national strategy for hydrogen. [32] As part of this, they see an opportunity to assist Japan with its intentions for hydrogen use, starting with providing it with shipped blue hydrogen. In November 2019, the Australian Renewable Energy Agency (ARENA) today announced a funding round of up to A$70 million to help fast track the development of renewable hydrogen in Australia. ARENA's hydrogen funding round is expected to play a material role in supporting commercial-scale deployments of renewable hydrogen in Australia. [31] In May 2020 the Australian government directed the Clean Energy Finance Corporation (CEFC) in the country to make A$300 million available to support the growth of an innovative, safe and competitive Australian hydrogen industry. [63]

The New Zealand government opened its Vision for hydrogen power to public consultation in September and October 2019. [33]

Canada

Canada is active in this space, and sees potential in future green hydrogen markets, not just as a producer of the gas, based on abundant renewable resources, but also as a manufacturer of fuel cells. Natural Resources Canada, a federal department, outlined the opportunity in a paper this month. [29]

China

In China, green hydrogen is seen as a potential way of decarbonising transportation. The country's targets include 5,000 fuel-cell vehicles by 2020, growing to 1 million vehicles by 2030. [29]

Tax exemptions exist in China for hydrogen-powered vehicles. The number of manufacturers involved in components for fuel cells or other elements of the hydrogen economy is growing, and fuelling stations are being set up in certain parts of the country to service the anticipated fuel-cell vehicles that will come onto the market. [29]

Researchers from the Chinese Academy of Sciences of Beijing and Tsinghua University (Beijing) have investigated real-time, on-demand hydrogen generation for use in fuel cells. They describe their results in the Journal of Renewable and Sustainable Energy. [50]
The researchers used an alloy -- a combination of metals -- of gallium, indium, tin and bismuth to generate hydrogen. "Compared with traditional power generation methods, PEMFC inherits a higher conversion efficiency," according to author Jing Liu, a professor at the Chinese Academy of Sciences and Tsinghua University. "It could start rapidly and run quietly. Moreover, a key benefit to this process is that the only product it generates is water, making it environmentally friendly." [50]

India

In India, the national government has said it intends to use hydrogen-based fuel technology to help combat pollution. [45] The IEA is working with the Indian government to review options. It will require some significant changes to put into place. [52]

Europe (various countries)

Across Europe, several countries are working on green hydrogen initiatives, as identified by the Hydrogen Council.

Germany, the UK, France and the Netherlands are leading lights. Germany is already home to the first hydrogen-powered train, and in July 2019 the Economy Ministry Peter Altmaier declared a goal for the nation to become “the number one in the world” for the use of hydrogen technology. [53]

In Germany, hydrogen is being seen as an important option to help to fill an energy gap arising from the impending closure of nuclear stations and the phase-out of coal-fired power.

As part of continuing to focus on its emission cuts, the German government announced in July 2019 that 20 new research laboratories will receive a total EUR100 million a year to test new hydrogen technologies for industrial-scale applications. Additional money is being allocated for labs in “structural change” regions, including those most affected by the nations’ emissions shift. [53]

In the UK, in March 2020 10 companies announced a taskforce that has been formed to work with the UK government to fast-track innovation and investment in hydrogen energy projects. [54]

The UK is host to several hydrogen projects, including a ground-breaking £7 million pilot to inject hydrogen into a gas network to heat homes. The UK government has announced new funding for hydrogen via a Hydrogen Supply Programme and Industrial Fuel Switching Competition. [54]

NGOs, Environmental campaigners and Not for Profit Foundations

Activists such as Greenpeace comment on hydrogen initiatives and plans around the world, as part of promoting better outcomes for the planet. They are a positive influence on how policies move forward, an example being their review of the New Zealand government’s hydrogen strategy. [34]

Academic Research and Scientists

The global academic and scientific community is working closely with governments and businesses to review the technological options for producing green hydrogen as an energy source. They are often supported by grants by governments and public bodies.

Referring to our point about energy storage earlier, one university in Australia has been looking at how to use hydrogen as an "energy vector" to transport solar photovoltaic energy from the Pilbara to the fuel tank of a hydrogen-powered car on the streets of Tokyo.

Elsewhere, a project in Germany has been looking at how electrolysis and the generation of hydrogen from the outputs of air conditioning systems could be combined with captured CO_2 to produce hydrocarbon fuels via a technique called "Fischer-Tropsch catalysis", or similar approaches in modular conversion systems. [42]

Financiers and Investors

From an investor standpoint, there is increasing evidence that investors want to see evidence of well-thought-out plans to reduce carbon emissions, and to tackle all other aspects of sustainability. How businesses use and consume energy is part of this. Investors will doubtless want to see whether green hydrogen energy can be cost-competitive in comparison to other energy options.

Hydrogen industry associations and producers

The Hydrogen Council is a leading advocate of using new, green hydrogen as a part of the world's energy mix. They are a body that is supported by many large organisations.

Fuel Cells and Hydrogen 2 Joint Undertaking is an initiative by the Council of the European Union. Since 2014, it has been working with some €1.3 billion of funding.

Businesses

Businesses in different sectors are investing in hydrogen technology. A selection of examples are provided below (in addition to the examples provided earlier).

<u>Energy – Shell</u>

Shell has been working on developing hydrogen as an energy carrier for a while.

In 2017, the company became the first branded fuel retailer to sell hydrogen at one of its retail sites in the UK. The hydrogen refuelling stations in Cobham and Beaconsfield, in partnership with ITM, use hydrogen produced on site using electricity from renewable sources. [35]

Source: [Shell]

In Germany, Shell is part of a joint venture called H2 Mobility with industrial gas manufacturers, Air Liquide and Linde, car manufacturer, Daimler, and energy companies, Total and OMV, to develop a nationwide network of hydrogen refuelling stations. They are developing hydrogen stations in the UK, in the Netherlands, and in Canada.

In the USA, Shell currently has four hydrogen filling stations in California and is currently working in partnership with Toyota, with the support of the State of California, to further develop its hydrogen refuelling network.

Shell is also involved with other hydrogen energy initiatives. In the Netherlands, the Dutch transmission system operator Enexis and other partners are looking at a feasibility study is being conducted to consider hydrogen production at sites owned by NAM – a JV formed by Shell and ExxonMobil. [43]

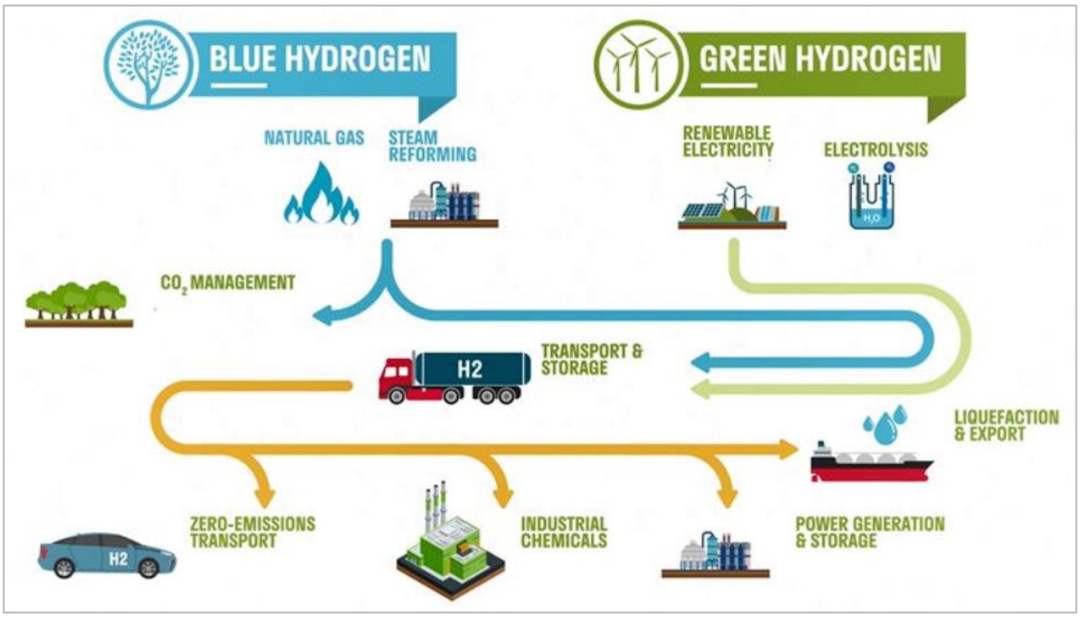
Since 2018, Shell has been part of a Californian consortium to develop three new large-capacity refuelling stations for heavy-duty hydrogen fuel-cell trucks being developed by Toyota and Kenworth Truck Company. One of these stations will use hydrogen made from biogas, which is natural gas made from renewable sources.

Energy – Woodside

Woodside's vision is firstly about blue and green hydrogen. Recognising that blue is much cheaper today, they believe the market and infrastructure can be developed economically, and production can shift to green once costs become competitive and when demand grows. [46]

To grow demand, the second aspect of their vision is about choice. For example, consumers being able to watch a video about where their green energy comes from as they fill up or seeing an eco-restoration project funded by a carbon offset. [46]

The third aspect of their vision is that fuel stations become Energy Hubs. Hydrogen and rapid EV chargers could capture excess renewable energy from the grid to produce hydrogen and return it at peak times. Hydrogen fuel cells power the EV chargers. Consumers can get a credit for energy from the solar on their grid-connected homes.



Source: [Woodside]

Automotive – Audi

As mentioned earlier, Audi (owned by VW) are also in this market, with their h-tron vehicle. Their concept car is driven by a fuel cell which generates electricity from hydrogen. Audi says that it can produce hydrogen itself in its own power-to-gas plant using neutral, green electricity CO_2. With this idea, Audi is making an interesting proposal for the mobility of the future. [38]

A timescale for volume production of Audi FCEV models has yet to be announced, but Audi has said it could occur during the second half of 2020s.

The new fuel cell technology is developed through a cross-licensing agreement with Hyundai, which already sells the Nexo SUV. The two car makers announced they were joining forces on FCEV development in June 2018.

Steel production – ArcelorMittal, Thyssenkrupp, SSAB and Baowu

Steelmaking is an energy-intensive process. In the traditional process of making steel, iron is first extracted from its ore in blast furnaces at temperatures of up to 1,200 degrees Celsius using coke, a carbon-rich form of coal. One of the by-products of this process is carbon dioxide. By replacing coke with hydrogen, which the World Steel Association states is an important area of research and development, the main by-product of steelmaking is water rather than CO_2. This could have a significant impact on carbon emissions for the steel industry.

The world's largest steel producer, ArcelorMittal, is working on a demonstration plant in Hamburg with Midrex Technologies for the large-scale production and use of Direct Reduced Iron (DRI) made with 100% hydrogen as the reductant, in place of coking coal. [56]

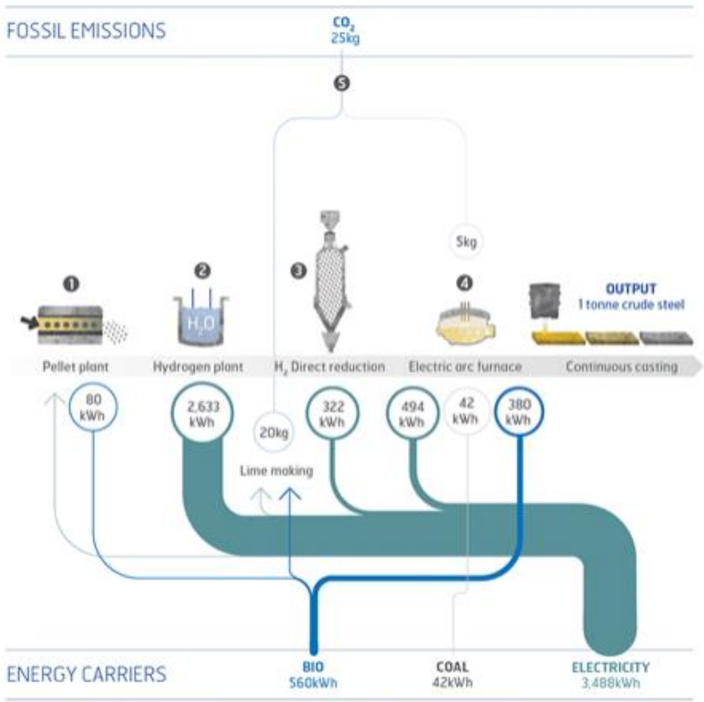
In the coming years, it is expected that the demonstration plant will produce about 100,000 tons of Direct Reduced Iron per year - initially with grey hydrogen sourced from natural gas. ArcelorMittal state that the intended conversion to green hydrogen (i.e. coming from renewable energy sources) should take place once it is available in sufficient quantities and at an economical cost. The economics could take some time to come to fruition. Energy for hydrogen production for the demonstration plant, for example, could come from wind farms off the coast of Northern Germany. [56]

Also in Germany, in November 2019 Thyssenkrupp completed a successful, first-of-its-kind demonstration of running a steel furnace completely on hydrogen. [68]

Similarly, Svenskt Stål AB (Swedish Steel, or SSAB), which is headquartered in Sweden and is partly owned by the government of Finland, announced in January 2020 that it would be making substantial investments to accelerate the transition of its steel furnaces to use emissions-free, renewable hydrogen. [57]

The efforts to move to using renewable hydrogen in steelmaking will have a significant impact on the emissions of the two Nordic countries with major SSAB operations. It is anticipated that there could be a reduction of 7 per cent of Finland's greenhouse gas emissions and up to 10 per cent of Sweden's emissions. [57]

The Chinese steelmaker, Baowu, is also investigating the process and investing in research and development for it. [58]

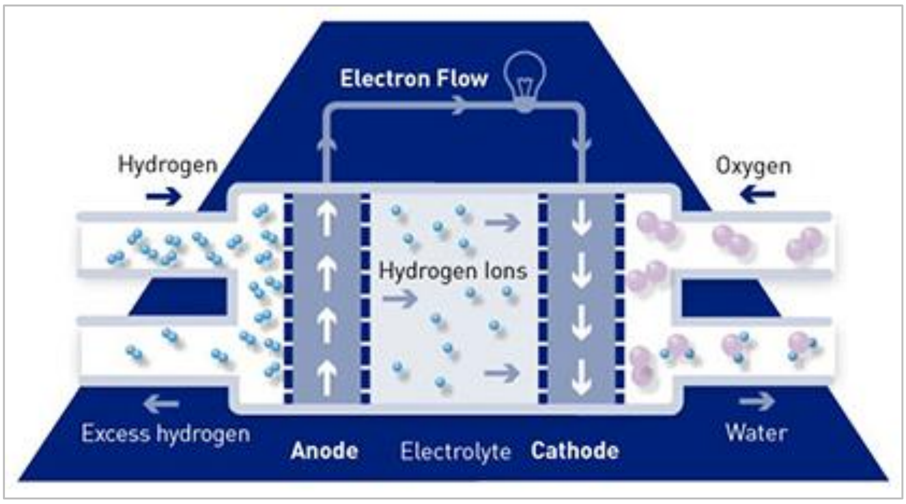


Breakdown of the steel production process using hydrogen. Credit: Hybrit

Mining – Anglo American

Fuel cells are a key part of the future of green hydrogen technology, and platinum plays a key role in the creation of hydrogen fuel cells. [36]
The international mining company, Anglo American, is committed to sustainable mining, and its Platinum business is the world's largest primary producer of platinum.

As the company describes on its website as part of its FutureSmart Mining™ strategy, platinum metal is often used as part of the anode catalyst in a hydrogen fuel cell. When pressurised hydrogen enters the fuel cell at the anode, the platinum-containing catalyst separates it into protons and electrons. [37]



Source: [Anglo American]

What can Risk and Operations teams in various industries do?

Risk Managers and Risk Advisors in all organisations can play a valuable role in working out how they can achieve their sustainability objectives, and how to take and manage risks to do so. Sustainability is business-critical today – from investors that are demanding to see strategies are in place, to employees who want to work for a business that demonstrates purpose. Risk professionals can be trusted advisors who can help people to achieve objectives, using risk-informed decision-making and risk tools and techniques to work out which risks (opportunities) to take and which risks (threats) need to be managed.

With regard to any organisation's use of energy, Risk Managers and Risk teams can work with their colleagues in Sustainability and Operations to think through how, for their organisation's particular circumstances, they should approach their situation. Perhaps there are specific opportunities for an organisation to procure energy from organisations that are investing in green hydrogen, and / or be involved in its production – if you can demonstrate a good cost-benefit to doing so. Using good Risk tools and thinking carefully through your options can help you to work out what is most feasible and impactful to you, now and in future.

Consideration	Ideas and thoughts for consideration
1. What exactly do you do?	• What do you design and / or produce, and how much energy do you use in your business processes? Whether you produce physical assets or information-based assets, what can you do to ensure your consumption of energy uses cost-effective sustainable sources, which may include hydrogen? • In your use of energy, are you investigating options to use green hydrogen? Is it being seen as a cost-effective solution – now or in the future? • If you use certain products, can hydrogen be involved in the production process as a sustainable solution (such as the example provided for steelmaking)?
2. How does your business use, procure or produce energy, and can hydrogen be part of your energy mix?	• What type of energy do you use and require, in all your facilities? • Would hydrogen fuel cells be an option for you, for one or more purposes – if not now, maybe in future (comparing its costs and benefits to other energy sources)? • Have you spoken to any businesses involved in green hydrogen production to find out how you might be able to use it as part of your energy mix?
3. Do you have opportunities to work with clients on green hydrogen?	• Would any of your clients be interested in seeing how green hydrogen can be used as part of a cost-effective sustainability approach to energy use? • Are some of them already using green hydrogen?

Consideration	Ideas and thoughts for consideration
4. Do you have the opportunity to be involved in any research?	• Are there opportunities for you to be involved in industry-specific or cross-industry research into the benefits of green hydrogen?
5. What does your supply chain look like?	• In our modern world, we have spent many years honing our supply chains to be as real-time and efficient as possible. However, we do not always look at how our supply chain uses energy to produce what they supply us with. • Do you know if parts of your supply chain are using hydrogen in their energy mix, and if so, how?
6. Where do you operate in the world?	• If you operate in developed economies, many of them are already investing in hydrogen research and technology. • If you operate in fast-growing emerging economies (for example, Asia, Africa and India), how can you play a part in helping people and businesses to think through how to ensure sustainable energy sources as used, and can hydrogen be part of the mix?
7. Do you know your investor expectations, for sustainability of businesses they invest in?	• Do your investors have expectations about your energy footprint? • Are any of them talking about the use of hydrogen? • Are you engaging with them in how hydrogen could be part of your energy mix, and the positive impact it could have for their investment funds?
8. Do you know how government policy is changing, and how it could affect what you do?	• Government policies around the world towards the use of energy are changing. Are you aware of the regulations that currently exist for the potential to use hydrogen as part of the energy mix and how they could change? What risks – threats and opportunities – does this present for your organisation? • Are there any specific permits or regulations to be aware of if you want to use hydrogen as part of your energy mix? • Are there any incentives available for you to be involved in government initiatives involving the use of hydrogen, particularly green hydrogen?
9. Sustainability reporting	• Have you thought about how activities in green hydrogen production / use may help you with your sustainability reporting and your sustainability commitments?

Conclusion

This paper has discussed how hydrogen may help organisations, large and small, in numerous industries to play their part in improving how the world produces and consumes energy, for the betterment of the planet. Given the opportunities that hydrogen presents, we should all be thinking about how we may able to make cost-effective use of it.

That said, challenges remain, particularly to ensure that the use of hydrogen – especially green hydrogen – is cost-competitive when compared to other options, and that it truly shows sustainable benefits. How the use of hydrogen scales over time will be an important determinant of how the industry grows.

Governments around the world play an important role in the judicious use of policy-making to encourage the right type of investments in technology to ensure hydrogen is cost-effective. Evidence exists that investments are making a difference. Industries and businesses need to be clear about the pros and cons of using hydrogen, and to work out if and how it can be a good solution as part of their energy mix.

Further suggested reading and watching

The Hydrogen Council has some very interesting and useful information on hydrogen as a sustainable energy and fuel source.

- FAQ
- Infographics
- Articles

The H2FUTURE project in Europe is a very interesting initiative with six major players to generate green hydrogen from electricity from renewable energy sources.

The International Energy Agency (IEA) has released two very interesting and detailed reports in May and June 2019, the first on Tracking Energy Integration and the second (circa 200 pages) called The Future of Hydrogen.

A report published by the Hydrogen Council in January 2020 titled Path to Hydrogen Competitiveness: A Cost Perspective, forecasts that the cost of hydrogen solutions will fall sharply within the next decade. [49] According to the report, this cost trajectory can be attributed mainly to scale-up that positively impacts the three main cost drivers:

1. Strong fall in the cost of production low carbon and renewable hydrogen;
2. Lower distribution and refuelling costs thanks to higher load utilisation and scale effect on infrastructure utilisation;
3. Dramatic drop in the cost of components for end-use equipment under scaling up of manufacturing;

In May 2020, Hydrogen Europe published a paper, "Post COVID-19 and the Hydrogen Sector - A Hydrogen Europe Analysis", to discuss the role of hydrogen in the energy mix post COVID-19.

KPMG have published a detailed "Hydrogen Communities & H2City Tool" that you can download to assess hydrogen needs in a city.

About the author

Gareth Byatt is Principal Consultant of Risk Insight Consulting. He works around the world with clients in various industries and sectors, many of which require large amounts of energy to produce their outputs.

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