October 2022

Hydrogen and the energy transition: One molecule to rule them all?

- Although it is too-often hyped as a climate change silver bullet, hydrogen is a credible part of the solutions to decarbonise our energy system, if it is itself produced without carbon
- There is an intimate alignment between green hydrogen and renewable electricity as the latter is the key enabler of the former
- Direct electrification is a superior proposition and should be favoured whenever possible
- A first step is to decarbonise carbon-intensive hydrogen production and to ensure that growth is dedicated to applications where alternatives are scarce, such as heavy-duty road transportation, long-haul shipping, or steel making
- Green hydrogen is not cost competitive today but is expected to be in a decade. It is however important to think in terms of delivered cost to the end users
- The real objective is to build a hydrogen ecosystem, which will require investments in transport and storage infrastructure
- Hydrogen does not exist in a vacuum and competing technologies may prove more effective. For instance, progress in battery technology, most notably solid-state lithium-ion batteries, or even in fusion will affect our view of the attractiveness of hydrogen in certain applications
- Hydrogen is a relatively inefficient energy carrier given the energy required to produce and transport it. Society – including engineers and economists – will have to accept that a hydrogen economy may be ostensibly less efficient than a fossil fuel economy, but that this is not true once you factor in the effect of carbon emissions
- We argues that opportunities for investors arise more in renewable electricity and integrated hydrogen supply chain areas than in equipment suppliers

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The Intergovernmental Panel on Climate Change (IPCC) made clear in its August 2021 report that humankind is making a dramatic contribution to global warming through emissions of greenhouse gases, mostly carbon dioxide (CO_2) and methane (CH_4).[1] To contain the increase in temperature and limit disruptions to our planet's ecosystem it is necessary to reduce those emissions by moving to a decarbonised economy.

Right now, and despite increasing efforts from governments, businesses and investors, we remain locked in the fossil fuel-based economy that has powered our world since the industrial revolution. Coal, crude oil and natural gas – which together account for about 80% of emissions – have offered us high energy density and relative ease of transport and storage.[2]

The energy transition is our effort to switch to other forms of primary energy and other energy vectors, but it also is much more than this.[3] As our economies and societies transition, we will pay higher prices as the cost of carbon is made visible. In the language of economists, we will internalise an externality. Living with two energy systems will be an additional source of costs, but there are opportunities for growth in the transition too.[4]

It is also a behavioural and social transition. We will have to make hard choices on what we consume and how we consume it. We will have to redefine what we count as "basic" needs and "luxury" habits. The on-tap availability of energy, goods, and services could be questioned, at least in rich countries with high emissions per capita.

The breadth of this challenge demands a breadth of solutions, and in this context, hydrogen – or to be precise, di-hydrogen (H_2) – has gained more prominence in recent years among the many tools and levers that can drive decarbonisation.[5] We believe hydrogen has the potential to be a carbon-free source of electricity, fuel, a long-term energy storage medium, or a raw material – but currently production is relatively carbon-intensive and the hydrogen created largely destined for use in industrial processes only tangentially linked to the energy transition.

In this note, we look at how that dynamic may change and how this simple molecule might evolve to become a fundamental part of the transition. Most notably, we will explore how so-called green hydrogen, produced through electrolysis of water with renewable electricity, might become an attractive prospect for investors.

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[1] "It is unequivocal that human influence has warmed the atmosphere, ocean and land", IPCC 6th Assessment Report

[2] Global Energy Review: CO2 Emissions in 2021, IEA

[3] Primary energy is the energy that is harvested directly from natural resources, e.g. coal, crude oil. An energy vector or energy carrier allows the transfer, in space and time, of a quantity of energy; e.g. gasoline, electricity, hydrogen. Energy Education, University of Calgary

[4] Climate change - Cost of inaction - Axa-im

[5] For simplicity, we will use the term hydrogen instead of di-hydrogen

Hydrogen 101

The hydrogen atom is the most abundant element in the universe. It is the simplest atom, with one proton and one electron, and the lightest element in the periodic table.[6] On Earth, hydrogen is found in chemical compounds, most notably in water (H_20) and methane. In its gaseous form, hydrogen has a high energy content, but a low density. It may need to be liquefied or compressed for certain uses, but compared to other fuels, pound for pound, hydrogen contains much more energy – this is why it is part of the energy transition debate.

The first table opposite highlights how hydrogen's main physical characteristics compare to other energy sources

About 90 million tonnes (MT) of hydrogen were produced in 2020 according to the International Energy Agency (IEA). Some 72MT were produced from dedicated plants and the balance mostly as a by-product of oil refining processes. Demand has grown by 50% since 2000.

The largest end-market is in refining where 40MT was used in 2020, mainly to remove sulphur from fuels, with 33MT used to produce ammonia, mostly for fertilisers. The two other significant uses are for methanol and in iron ore production.

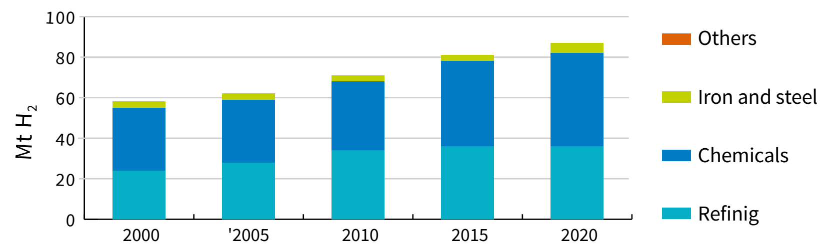
Selected Hydrogen comparisons

Property	Hydrogen	Comparison
Density (gaseous)	0.089 kg/m3 (0°C, 1 bar)	1/10 of natural gas
Density (liquid)	70.79 kg/m³ (-253°C, 1 bar))	1/6 of natural gas
Boiling point	-252.76°C (1bar)	90°C below LNG
Energy per unit of mass (LHV)	120.1 MJ/kg	3x that of gasoline
Energy density (ambient cond., LHV)	0.01 MJ/L	1/3 natural gas
Specific energy (liquefied, LHV)	8.5 MJ/L	1/3 of LNG
Flame velocity	346 cm/s	8x methane
Ignition range	4 —77% in air by volume	6x wider than methane
Autoignition temperature	585°C	220°C for gasoline
Ignition energy	0.02 MJ	1/10 of methane

Notes: cm/S = centimetre per second, kg/m³ = kilograms per cubic metre, LHV = lower heating value, MJ = megjoule, MJ/kg = megajoules per kilogram, MJ/L = megajoules per litre.

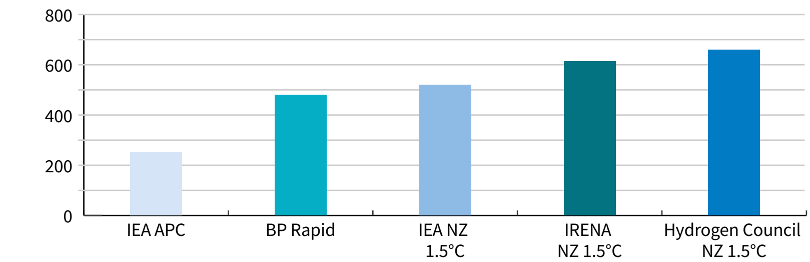
Source: The Future of Hydrogen, IEA, 2019

Hydrogen demand by sector, 2000-2020



Source: Global Hydrogen Review, IEA, October 2021

Estimates for hydrogen demand in 2050



Sources: IEA, IRENA, Hydrogen Council, BP[8]

Of the 72MT derived from dedicated plants in 2020, virtually all of the hydrogen was produced from fossil fuels, mostly methane (75%) – the main component of natural gas – and coal (24%). Methane-based plants can be found everywhere on the globe, but the coal-based method is predominantly used in China. Overall, the IEA reckons that 6% of the world's natural gas and 2% of the world's coal are used to produce hydrogen.

Rapid growth in production is widely predicted. Various agencies and forecasters envisage an annual market of between 480MT and 660MT by 2050, equivalent to more than seven-fold expansion at the upper end. The IEA has also a lower growth scenario, with the market reaching 250MT by 2050 based solely on announced country pledges (APC) linked to the Paris Agreement.[7]

In all scenarios, the hydrogen is fully produced through decarbonised or low carbon processes, compared to less than 1% currently. The main difference between the forecasts is the level of penetration of hydrogen in passenger cars.

However, when looking at the list of hydrogen projects identified by the IEA (updated as of October 2021[9]), there is strong but insufficient momentum. There appear to be many projects, with more announced regularly, but prospective additional capacity is currently estimated at about 12-14MT for 2030. That means the development pipeline is sharply undershooting all the scenarios presented above, bar the baseline IEA scenario.

[6] To be chemically strict, the H+ ion, made of only one proton, is even simpler

[7] Announced country pledges are emission reduction pledges made by countries after the COP21 in Paris in 2015 and updated in Glasgow at the COP26 in 2021. According to the 2021 UNEP Emissions Gap Report and NGO Climate Action Tracker, the world is on track for a warming significantly above 2°C based on those pledges

[8] NZ: Net Zero.The Hydrogen Council is an initiative made of more than 130 companies to promote hydrogen; Hydrogen for Net-Zero. In its Rapid scenario, BP factors in a reduction of global emissions by 70% by 2050; BP energy outlook. IEA Net Zero 1,5°C scenario.

[9] Hydrogen Projects Database - Data product - IEA

Hydrogen's production processes

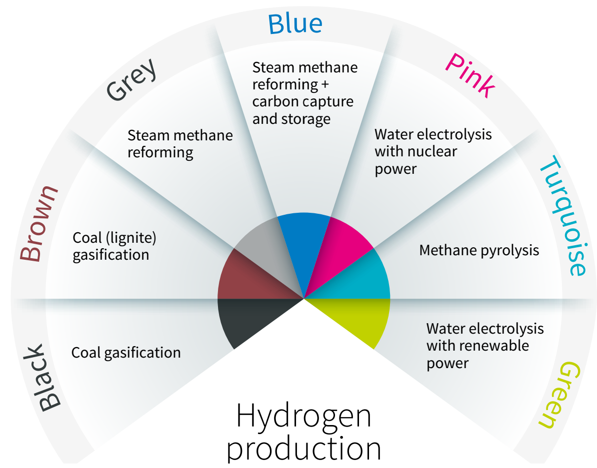
Hydrogen is produced by splitting apart molecules in which it is a component. Fossil fuels have been the main feedstock as they are made primarily of carbon and hydrogen. The water molecule – made of oxygen and hydrogen – is another significant potential reservoir.

When the source molecules are split, hydrogen is produced, but the other elements are released. Hence, the production of hydrogen from fossil fuels leads to significant carbon emissions, while splitting water leads to benign emissions of oxygen.

A typical methane plant produces 10 units of CO_2 per unit of hydrogen, and a coal plant 19 units. There are a handful of methane plants with carbon capture and storage (CCS) installed, which can reduce the carbon footprint to between 1-4 units of CO_2, but they account for less than 1% of total production. Emissions from water electrolysis depend on the electricity supply. A coal-powered electrolyser will be "dirty" while there will be zero carbon for one powered by renewable electricity.

The different production processes of hydrogen have been given colours related to their vastly different carbon intensities. The following table matches processes and colours, including production pathways such as methane pyrolysis still at the research and development phase.

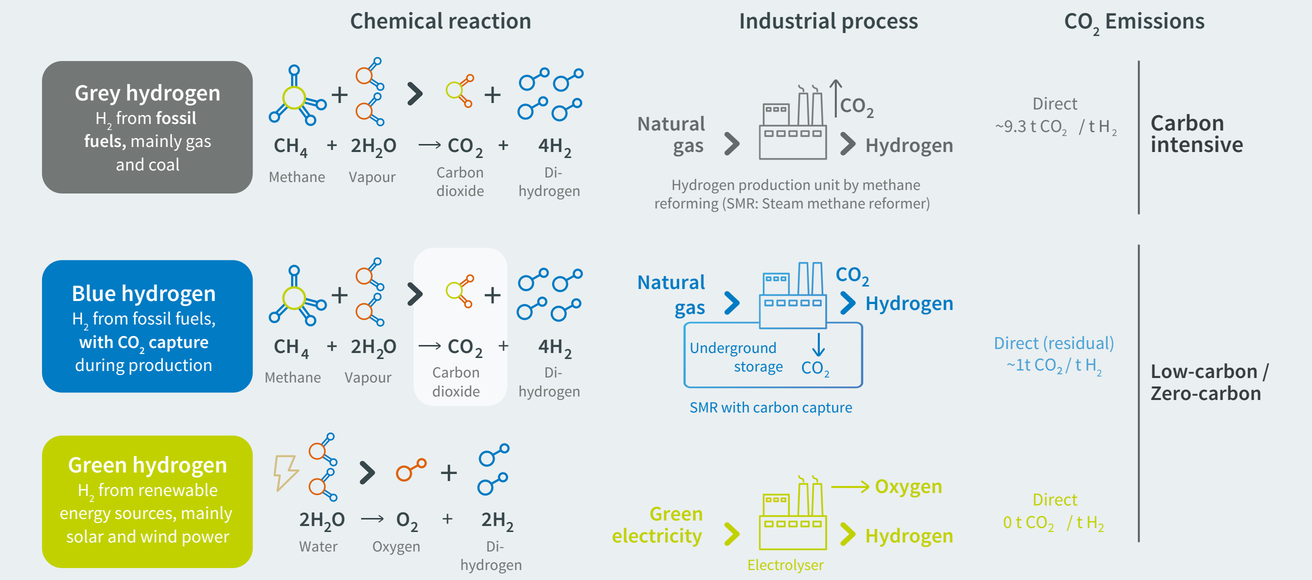
The colours of hydrogen



Overall, given the current production mix, dedicated hydrogen plants worldwide generate around 900MT of CO_2 emissions, equivalent to 2.5% of global emissions, or 40% more than Germany's CO_2 emissions.[10] While hydrogen is presented as a solution to decarbonise, today it remains a very carbon-intensive product. To have a viable place in the energy transition, the mix must switch decisively towards production without carbon.

The following schematic details the main processes:

Hydrogen industrial processes



Source: Total Energies Energy Landscape. CCS assumes 90% capture rate in this example

[10] BP Statistical Review of World Energy 2022

Focus on green hydrogen

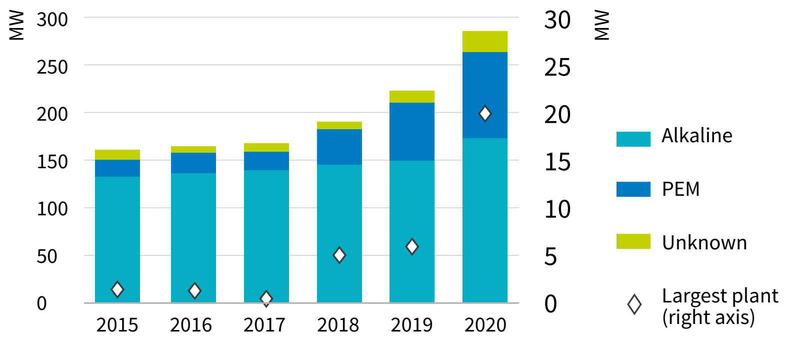
Most studies around hydrogen call for a massive deployment of green hydrogen. However, according to the IEA, green hydrogen accounted for just 0.03% of total production in 2020. Installed electrolysis capacity was 290MW. If the 2020 production volume of 90MT was produced through electrolysis, it would require capacity of about 950GW.[11]

Two technologies dominate the electrolysis landscape: Alkaline, which originated in the 19th century, and, proton exchange membrane or PEM – which was first developed during the 1940-50s. Both are well proven and commercially viable, with PEM having more room to further improve than the very mature alkaline technology. Two other potential technologies exist – Solid Oxide Electrolysis Cell (SOEC) and Anion Exchange Membrane (AEM) – but these are still at the development phase.

All electrolysis technologies function with the same fundamental process: an electric current pass between an anode and a cathode and splits purified water into hydrogen and oxygen. They differ on temperature and pressure, and on the materials used for the electrodes and the electrolyte.

With more than 140MW of installed capacity, alkaline is the dominant technology.[12] However, PEM is gaining market share, notably thanks to its ability to power on and off extremely rapidly, a favourable feature considering the intermittency of renewable electricity supply.

Global installed electrolysis capacity



Source: Global Hydrogen Review, IEA, October 2021

The following table present the main strengths and weaknesses of alkaline and PEM technologies:

Key strengths and weaknesses of electrolyser tech

	Alkaline Electrolyser	PEM Electrolyser
Commercial status	Mature	Commercial, fast growth
Electrolyser electrical efficiency kWh/kg hycrogen	Today 48 – 53 2030 47 – 51 Long term 42 – 48	Today 56 – 59 2030 49 – 53 Long term 45 – 50
Operating temperature (°C)	60 – 80	50 – 80
Plant footprint m^2 : kW	0.095	0.048
Characteristics	• Slower dynamic response	• Faster dynamic response
Implications	• Less well suited to **intermittent power supply** (e.g. renewables) - likely to be over come by innovation for faster ramping and batteries to smooth short term variations.	• Well suited to a **variable electricity supply** (e.g. intermittent renewables) • Suitable for voltage regulation services
Stack lifetime (2030)	• 90,000 – 100,000	• 60,000-90,000
Major producers (non-exhaustive)	• Suzhou Jingli, Thyssenkrupp, Nel	• Siemens, ITM Power, Cummins

Source: "Making the Hydrogen Economy Possible", Energy Transitions Commission, 2021

[11] Thyssenkrupp nucera CMD - January 2022, page 30

[12] Electrolysis capacity is quoted in watts while hydrogen production is in tonnes. The chemical formula of water electrolysis is as follows: H_2O (liquid) + 237.2 kJ/mole electricity + 48.6 kJ/mole heat → H_2 + ½ O_2. The final production of hydrogen will depend on the number of hours an electrolyser is running and on the efficiency of the system

Present and future costs

The key cost point to assess the competitiveness of hydrogen is the delivered cost to the end-user. This is relevant to compare hydrogen to other energy sources and energy carriers (gasoline, diesel, or natural gas), and also to different production pathways – green, blue or grey. Production cost is the key variable as the logistics costs of hydrogen are agnostic to its 'colour'.

The cost structure of grey hydrogen is well understood and heavily depends on the price of natural gas. A range of $1-$2/kg is widely acknowledged. For blue hydrogen, the cost of CCS has to be added. A range of $1.5-$2.5/kg is typical.[13]

For green hydrogen, the cost is highly dependent on the electrolyser cost, more precisely on the investment per kWh of capacity, and the electricity cost. In terms of the impact of the method of production, alkaline is currently cheaper than PEM but is expected to experience a smaller decline in costs. There are also regional differences depending on local factors. The cost range is much wider than for grey hydrogen as projects are smaller and located in regions with different conditions for renewable electricity.

As a result, the best green hydrogen projects show a cost of $2.5/kg – mostly with very cheap power – while small/high-power-cost projects are above $5/kg. It is important to keep in mind that current production volumes are very small and the sample size is limited. [14]

Production costs are expected to fall thanks to:

- **Declining cost of renewable electricity:** the unit costs of solar and onshore wind generation have fallen by respectively 85% and 56% between 2010 and 2020.[15] Expectations are for costs to fall further, notably for offshore wind. As seen in recent years, there will be regional differences in this trend

- **Declining capital intensity:** The cost of alkaline and PEM electrolysers falls in a range of $500-1,000/kW and $700-1,400/kW respectively today.[16] With growing scale – from single digit MW modules to above 100MW, larger projects where modules are stacked, and industrial development (which should deliver traditional efficiencies), the International Renewable Energy Agency (IRENA) expects the capital intensity to fall below $400/kW by 2030 and below $200/kW by 2050

- **Improved electrical efficiency:** A 1% change in efficiency translates into a 1.3% higher production, hence a lower unit cost. According to IRENA, current efficiencies are in a wide range of sub-50% to 80%, with often strong discrepancies between stated efficiencies and actual results. In its modelling, IRENA factors in an efficiency above 88% by 2050. There is ongoing research in this area to improve efficiencies.[17]

One important observation is that once the capital intensity falls below $400/kW, electricity becomes the primary cost driver, if the electrolyser is used more than 2,000 hours per annum (equivalent to about 12 weeks).

[13] Global Hydrogen Review, IEA, October 2021
[14] Ibid
[15] Renewable Power Generation Costs I 2020, IRENA, 2021
[16] Green Hydrogen Cost Reduction", IRENA 2020
[17] A high-performance capillary-fed electrolysis cell promises more cost-competitive renewable hydrogen | Nature Communications, March 2022

The following charts show the IRENA and Hydrogen Council views of cost trends for the next three decades.

The Hydrogen Council's cost pathway is more bullish as it relies on more favourable assumptions, notably a capital intensity of less than $250/kW by 2030.

The IEA, in its Global Hydrogen Review, forecasts rapidly declining costs as well. While it expects the same cost level for green hydrogen produced under optimal conditions, it expects a broader cost range, with highs of $3.9/kg by 2030 and $3.3/kg by 2050.

What those forecasts have in common, beside a sharp drop in unit costs, is that they do not forecast a cost, but cost ranges. That often-quoted witticism – "prediction is very difficult, especially if it is about the future" – also applies to hydrogen.

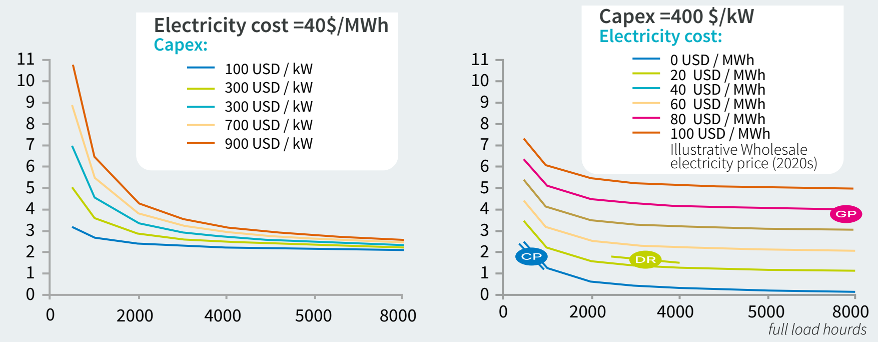
There are several variables to take into account – capital intensity, cost of electricity, location – which explains the variability in those forecasts. Location and electricty cost are connected. If we assume a standardised capital intensity, the difference in cost will come from the cost of electricity, and hence countries and regions with strong solar and wind resources will be advantaged. This could lead to the production of hydrogen being located not necessarily where customers are, but where the sun shines and the winds blow.

By and large, an average green hydrogen project is expected to become cost-competitive with grey and blue hydrogen sometime in the mid to late 2030s. However, large projects with access to very low-cost renewable power could be competitive in the very near future.

The comparison of green and grey hydrogen is usually done using normalised power and natural gas prices. The real world is however not normalised and shifting prices for those two components – driven by traditional supply/demand interactions, but also by geopolitical events – can paint a different picture at any given moment.

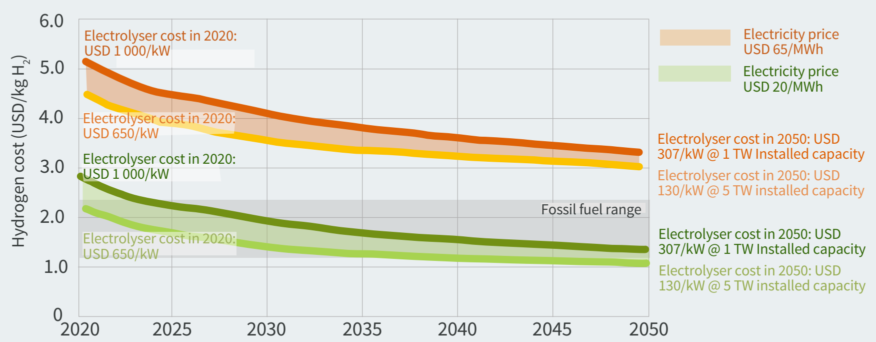
The introduction of a cost of carbon would change this cost dynamic as it would make grey hydrogen more expensive. In its modelling, with a carbon price of $50/tonne in 2030, the Hydrogen Council expects green hydrogen to reach cost parity by 2028 for the best locations and by the early 2030s for average locations.

Green hydrogen production costs $/kg



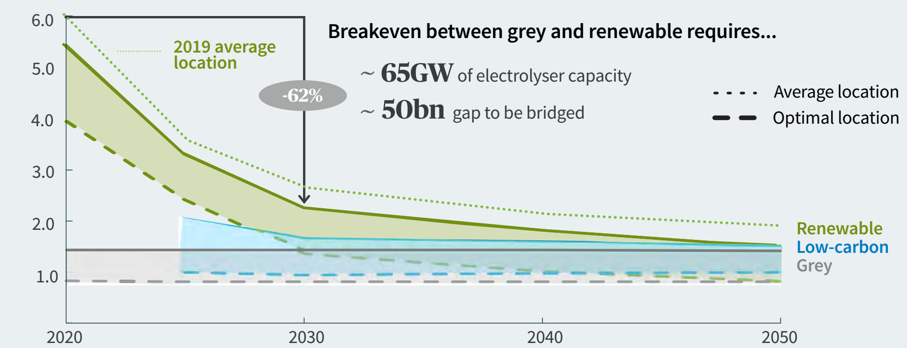
Source: "Making the Hydrogen Economy Possible", Energy Transitions Commission, 2021

Production cost of green hydrogen



Source: "Green Hydrogen Cost Reduction", IRENA 2020

Production cost of hydrogen USD/kg



Source: "Hydrogen Insights", Hydrogen Council, 2021[18]

[18] Key assumptions: gas price $2.6-$6.6/Mmbtu (Metric Million British Thermal Unit); power cost $/MWh $25-$73 (2020, $13-$37 (2030), $7-$25 (2050); low carbon hydrogen is blue hydrogen

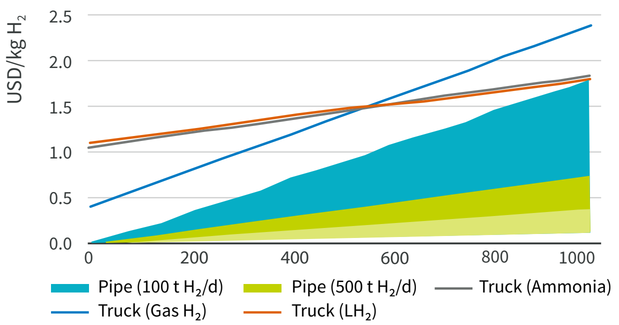
Cost for the end-users

End-customers do not pay the production price but a price that includes the entire distribution chain up to the delivery point. This delivered cost can be significantly higher, especially when production and consumption are geographically far apart or when small volumes are involved. This is clearly not relevant when hydrogen is produced on location, for instance at a refinery.

As discussed, the best locations to produce hydrogen may not be where the customers are. From a delivered cost perspective, there is an analysis to be made of the production and logistic costs to assess the optimal structure.

The IEA has produced the following chart, showing the relative merits of pipelines and trucking for land transportation.

Estimated transport costs per unit of hydrogen via different types of transport



Source: Global Hydrogen Review, IEA, October 2021.
H_2/d: hydrogen per day. LH_2: liquid hydrogen

Hydrogen can be transported under several forms: as a compressed gas, as a liquid (from a temperature of -252.76°C), or as a chemical compound such as ammonia. When compressed at 700 bars, hydrogen occupies 467x less space than at atmospheric pressure, and 789x less when liquefied.[19]

Overall, trucks are more competitive for volumes up to 10 tonnes per day. Pipelines are the most economical solution when greater scale is needed and long distances are involved. Shipping – for either liquefied hydrogen or ammonia – is for overseas trade and requires expensive dedicated vessels.

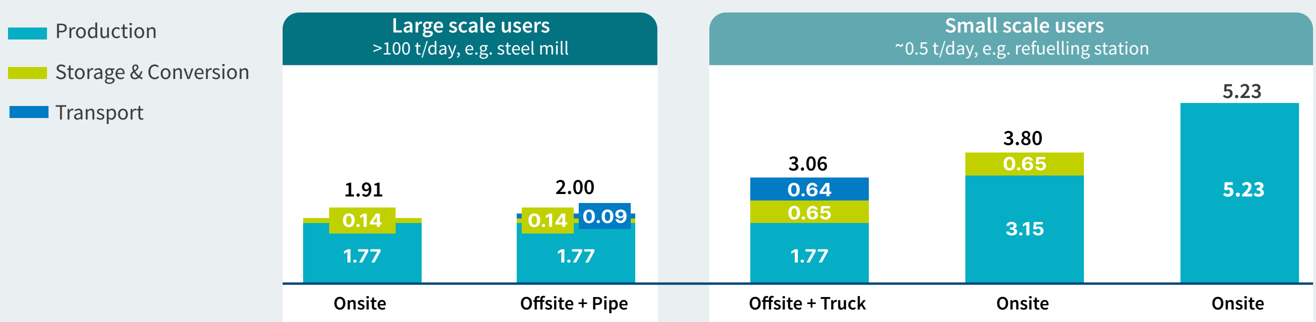
In all those options, there is an energy penalty as compression, liquefaction or conversion into ammonia consume energy. For instance, liquefying hydrogen consumes about a third of the energy that the hydrogen contains.[20] For large-scale users, onsite production is by far the most efficient solution as it only requires a short pipeline. This is why many hydrogen plants are located near refineries.

There are about 5,000km of hydrogen pipelines today, mostly on the US Gulf Coast and in Northern Europe, connecting clusters of industries, and operated by industrial gas companies.

Storage is another cost layer. The best way to store gaseous hydrogen is in salt caverns, a widely used technique for natural gas. There are currently four salt caverns in use for hydrogen – three in Texas and one in the UK – as well as several projects under consideration. As for any commodity, a well-functioning storage system is a necessity.

The following chart is an illustration of estimated delivered costs for alkaline-based production, in 2030:

"All-in" cost of delivered hydrogen including production, transport and storage, 2030 LCOH, $/kg



Source: “Making the Hydrogen Economy Possible”, Energy Transitions Commission, 2021[21]

[19] How is hydrogen stored? | Air Liquide Energies
[20] State of the art in hydrogen liquefaction , ISES Solar World Congress 2019
[21] LCOH: levelized cost of hydrogen. The most rightward column assumes grid power instead of renewable

Feedstock bottlenecks for green hydrogen?

Renewable electricity:

The viability of green hydrogen is dependent on the development of renewable electricity. As we have seen, water electrolysis is an electro-intensive process.

In its net zero scenario, the IEA expects green hydrogen to consume 10% of the world's electricity, from barely above 0% today. Whether or not this scenario comes to pass, the required growth in renewable electricity capacity in the coming decades is very significant. A key challenge is that hydrogen is one of the many end-markets for green power.

Electrification is one of the key levers – if not the key lever – to decarbonise our economies in any energy transition scenario, and competition for this power will be fierce, even more if growth in generation capacity is insufficient.

Water:

Water is essential to energy production, whether for thermal electricity – where steam is generated to move turbines, for coal production – where once extracted, coal is washed, or for oil – where water is used in enhanced recovery and processing.[22] Hydrogen is no exception:

- **Grey hydrogen:** according to the Hydrogen Council, the SMR process consumes between 13-14kg of water per kilo of hydrogen[23]
- **Green hydrogen:** at least 8.9kg of water are required to produce 1kg of hydrogen, assuming no losses in the electrolysis process.[24] However, according to ITM Power, a PEM electrolyser producer, total withdrawal is higher – to the tune of 17-20kg of water per kilo of hydrogen[25] – because water has to be cleaned and deionised first, which means that some 8-11kg are not consumed and immediately returned

Water for green hydrogen can be freshwater but can also be desalinated water – either sea water or brackish water from underground reservoirs – in water-stressed areas. This would increase the overall power consumption – as reverse osmosis technology, the leading desalination technology, uses 3.5-5kWh per cubic meter of clean water. It would also push up the cost – by $0.01-$0.02 per kg of hydrogen – of the entire process.[26] In other words, the use of desalination is a credible possibility and does not meaningfully impact the overall economic equation.

The subject of water and hydrogen requires a comparison of water intensity for different hydrogen production processes, relative to the water intensity of other sources of energy. Producing coal and crude oil is notoriously water intensive, and a shift to hydrogen could lower total water consumption.

Although it does not appear to be a problem on the technical and cost front, it could easily be more challenging on the social acceptance front at local community levels, where conflict of use could arise about water.

Metals:

Many metals are used in electrolysers, but nickel and iridium present specific constraints.

Alkaline electrolysers require large quantities of nickel, in common with lithium-ion batteries, where nickel is the main component of the cathode. While nickel is not scarce, rising demand from electric vehicles (EVs) could stress the market. The key challenge is for the mining industry to develop sufficient capacity that keeps pace with demand.

PEM electrolysers require platinum and iridium, two metals with limited production and a strong resource concentration in South Africa. Iridium, used to coat the anode of PEM electrolysers, is particularly rare. Supply issues could occur given the expected growth in green hydrogen. However, the industry's track record for steadily reducing the amounts of iridium required for a process is good and technical improvements to further reduce the intensity of use are expected (see here and here for instance).

[22] For more analyses on this topic, see World Energy Outlook 2016 - Excerpt - Water-Energy Nexus by the IEA or Thirsty energy - Oil&Gas Extraction by the World Bank
[23] Hydrogen-Council-Report_Decarbonization-Pathways_Part-1-Lifecycle-Assessment
[24] Given the relative molecular weights of hydrogen and oxygen, respectively 1 and 16 grams per mole
[25] Green Hydrogen Water Use, ITM Power
[26] Does the Green Hydrogen Economy Have a Water Problem?, American Chemical Society 2021

The case against hydrogen

"Been there, done that" is often heard when discussing hydrogen. Old timers and archivists will quickly point out that hydrogen has been "the next big thing" several times in the past. The tragic Hindenburg Zeppelin that burst into flames on 6 May 1937 has become somewhat emblematic of hydrogen's tricky past.

That accident highlights an important risk with hydrogen: It burns, and it burns well. Other fuels burn of course, but they do not require the complex infrastructure that hydrogen does. They notably do not need deep cryogeny or high compression.

In addition, the way hydrogen burns is different, notably it ignites more easily and the flame velocity is faster (x4.4 compared to methane).[27 28]

The H_2 molecule is small and can easily leak from pipes and tanks, hence a great focus on the physical integrity of infrastructure is needed, as well as specific safety and detection equipment for this invisible, tasteless, and odourless gas.

In the case of any large-scale leaks that increase the atmospheric concentration of H_2, there would be adverse consequences for global warming. By itself, the molecule has no direct warming potential. However, it has been shown that there are indirect impacts, most notably as hydrogen slows down the degradation of atmospheric methane, a very potent greenhouse gas, and also because it leads to a slight increase in water vapour in the atmosphere.[29] While this cannot be ignored and implies the need for robust operational standards for the hydrogen value chain, the benefits of using it to reduce CO_2 emissions do appear to be far greater.

Another point against hydrogen is its poor energy efficiency in several applications. Comparing the energy input and output along the hydrogen value chain – the energy required to produce and transport the hydrogen with the energy provided to the end-user – raises concerns that are explored below.

Beyond objective technical factors, as in many situations, the risk perception is at least as important as the actual risks. Social acceptance of hydrogen, especially if it is to spread widely, will be essential, as will be social acceptance of the renewable energy projects required to deliver scalable green hydrogen production.

[27] See table on page 3 and Hydrogen Compared with Other Fuels | Hydrogen Tools (H_2tools.org)
[28] Hydrogen for Power Generation Whitepaper, GE Power 2019
[29] Atmospheric implications of increased hydrogen use

Where hydrogen should be used... and where it should not

Before we start to carefully factor in things like economics and energy efficiency, hydrogen can have multiple and extended uses, mostly as a fuel that can be burned, as a molecule that can be turned into electricity, or as raw material for synthetic products. A first priority is to decarbonise existing hydrogen production.

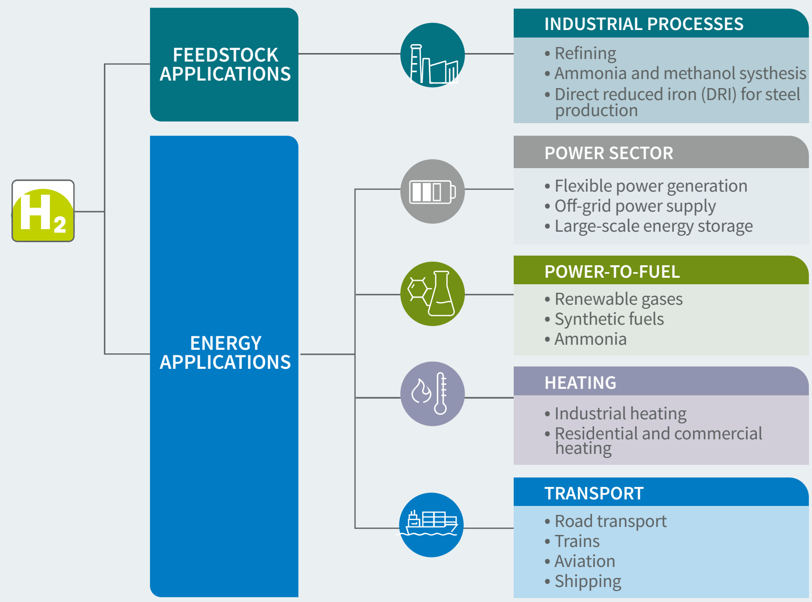
For new applications, one point that should be made in any analysis is to think in terms of entire value chains, emissions, economics, and technologies.

An important initial question is to ask whether hydrogen is the best lever to decarbonise a given application.

A key step then is to think in terms of energy efficiency. Between the initial input and the final consumption, there are many stages in the hydrogen value chain and many points of energy leakage. Hydrogen should be matched against alternative options, primarily direct electrification, as green hydrogen requires lots of electricity.

The case of smaller vehicles, i.e. passenger cars, is instructive. A battery electric car and a hydrogen fuelled car are both electric cars as they have electric engines. The first has a large battery rack, recharged from an external electricity supply, directly feeding the engine. The second has a compressed hydrogen fuel tank, fuel cells converting the hydrogen into electricity that feeds a small battery that feeds the engine. However, the energy yield, i.e. the share of energy that is used compared to the initial energy unput, is dramatically different and clearly in favour of battery electric cars.[30] In a study, Volkswagen showed that an EV had an overall electrical efficiency of 70%-90% while an hydrogen car stood at 25-35%.[31]

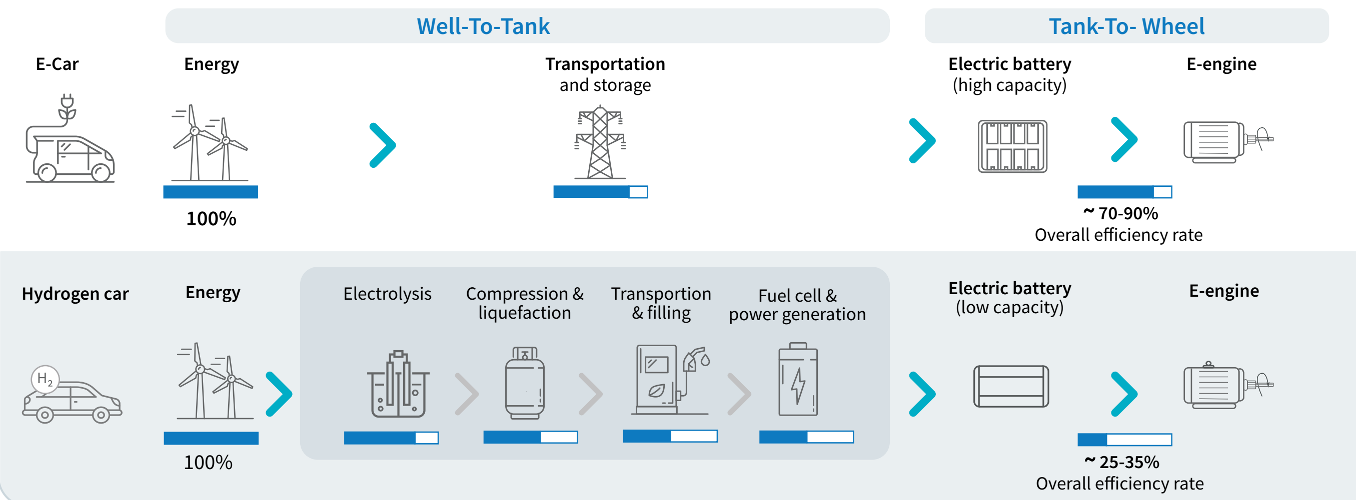
Actual and potential main uses for hydrogen



Source: "Geopolitics of the Energy Transformation – The Hydrogen Factor", IRENA, 2022

Hydrogen and electric drive

Efficiency rates in comparison using eco-friendly energy



[30] There are other elements to consider when comparing both technologies, such as fuelling time and range

[31] What's more efficient? Hydrogen or battery powered? (volkswagenag.com)

In many applications, direct electrification is a superior proposition, if it is technically feasible. It is important to use electricity, and preferably renewable electricity, for processes where the efficiency is the best. Hydrogen ought to be used for so-called hard-to-abate sectors, where there are no alternatives.

Let us highlight here several critical areas where we believe the merits of hydrogen are strong:

Heavy duty road transportation: Long distance trucking is diesel territory today. Electrification is not an option as the energy requirement of large trucks is too high compared to the capacity of batteries – the weight of the battery rack would be so high that the carrying capacity would be significantly reduced. This is why a hydrogen-based solution, using fuel cells, is seen as the most effective option.[32]

Progress in battery technologies could upend this analysis. State-of-the-art lithium-ion battery technology is not efficient enough today for heavy trucks going long distance, although it is appropriate for lighter trucks doing urban deliveries. Future progress, notably in solid state batteries, could change this.

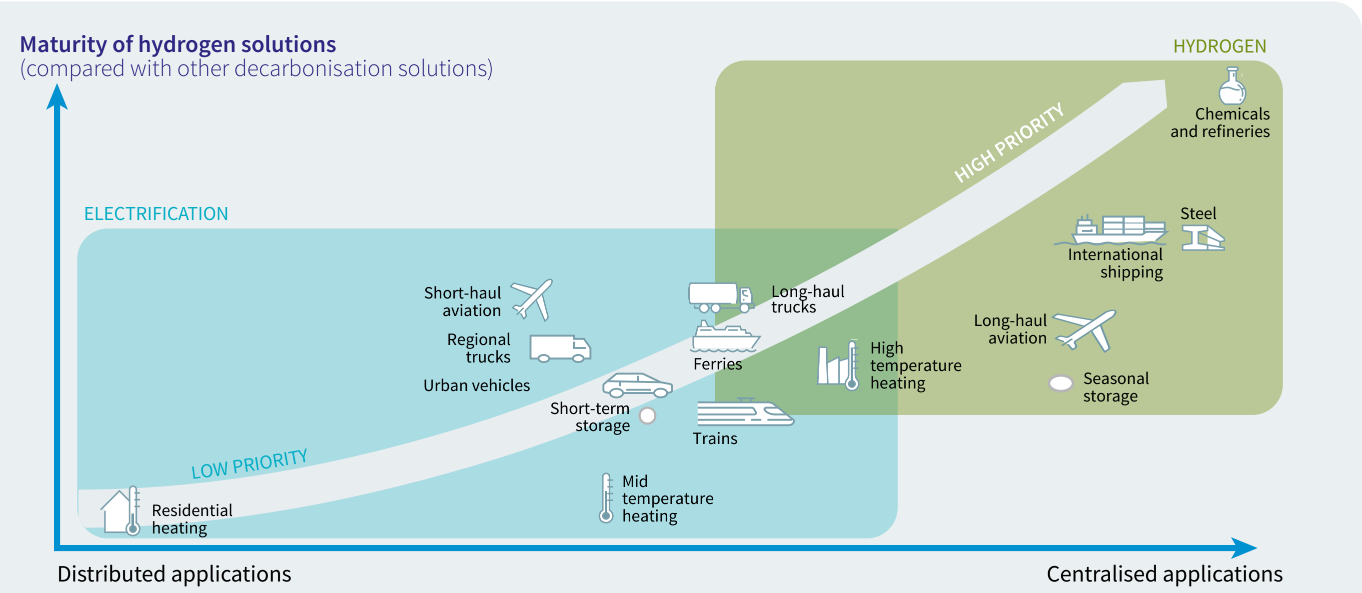
Long-haul shipping: International shipping accounts for about 2% of global CO_2 emissions.[33] While small and mid-sized vessels travelling short distance can be electrified, this is not the case for large long-haul ships given their weight and energy requirement. Container ships – the backbone of international trade as they move goods from manufacturing hubs in Asia to the rest of the world – need another solution.

Development of no-carbon fuels is necessary for those ships, and hydrogen, under the guise of NH_3, can help. The NH_3 molecule – three hydrogen and one nitrogen, i.e. ammonia – is already widely produced and traded. When it burns, it does not generate any CO_2. As we have seen, it is mostly used today to produce fertilisers, but it can be directly burned in engines. It would have to be green ammonia, produced with green hydrogen, and shipping companies would have to retrofit their fleet or invest in new ships. While the current cost is high, and higher than traditional marine fuels, this is a solution that could soon be available.[34]

Sustainability is not just about climate, and two issues with ammonia must be properly handled:

- Ammonia is toxic to humans. Safe handling is an obvious priority
- Burning ammonia generates NOx (nitrogen oxide), a gas harmful for human health, and advanced cleaning systems would be needed.[35][36]

The following chart is a good illustration of how we might view the relative merits of direct electrification versus electrification through hydrogen:



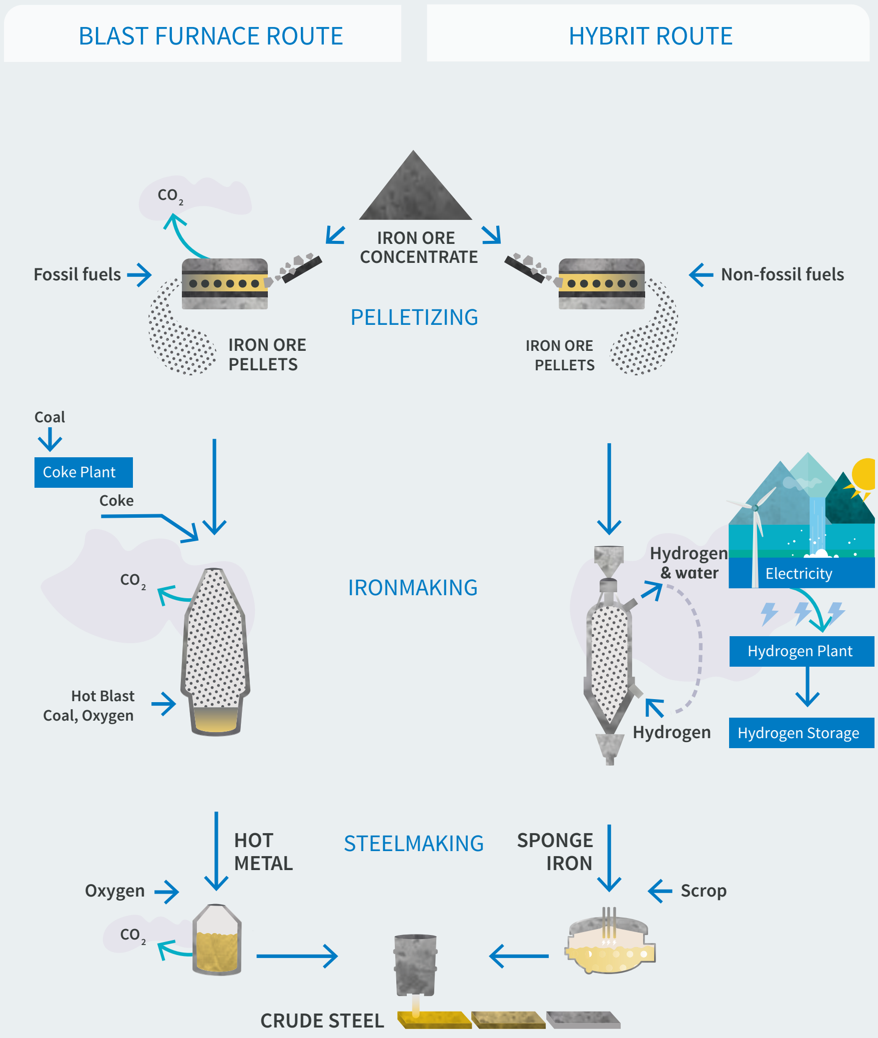
Source: "Geopolitics of the Energy Transformation – The Hydrogen Factor", IRENA, 2022

[32] Fuel Cell Hydrogen Trucks - Roland Berger
[33] International Shipping – Analysis - IEA
[34] The case for two-stroke ammonia engines - Maritime industry leaders to explore ammonia as marine fuel in Singapore , Maersk 2021
[35] Science and technology of ammonia combustion , Proceedings of the Combustion Institute 2019
[36] Nitrogen Oxides | Medical Management Guidelines | Toxic Substance Portal

Carbon steel: According to the IEA, the steel industry is deemed to be responsible for 7%-8% of the world's CO_2 emissions – a typical tonne of steel made in a blast furnace generates two tonnes of CO_2. This is because coke, made from metallurgical coal, is used to turn iron ore into iron by removing oxygen. It is feasible to use hydrogen instead of coke, with emissions of water vapour instead of CO_2. This requires access to hydrogen, but also a change in the industrial process (and therefore extra costs) to switch from blast furnaces to 'direct reduced iron' or DRI. The cost to produce steel without CO_2, also called green steel, will be higher than for traditional steel.[37]

Even so, companies have made moves in this area. Arcelor Mittal has announced several projects – in Belgium, Canada, France and Spain – to shift to DRI production.[38] SSAB, for its operations in Sweden, has brought forward its net zero steel target from 2045 to 2030 as it also goes the hydrogen way.[39]

The steel-making process



Source: SSAB - HYBRIT is the name of SSAB's hydrogen-based steel making process

Industrial heat: Certain industrial processes, such as making glass or producing cement, demand constant and very high levels of heat, up to 1,500°C. In general, this heat is generated by burning coal or natural gas, and sometimes biomass or waste. Burning hydrogen instead could be a technical possibility. It entails a change of equipment as, as we have described, hydrogen burns differently. It also entails handling corrosion risk as burning hydrogen generates water vapor.

Long term energy storage and power system balancing: A critical challenge in a decarbonised and electricity-dominated energy system is energy storage. Coal, crude oil, and natural gas are easily stored. Electricity is not. Battery farms exist and allow the storage of electrons but are limited in scale and durability. Hydrogen can be easily stored for months and years. Green hydrogen produced in times of excess renewable electricity supply can be stored and turned back later into electricity, either via fuel cells or direct combustion in gas turbines. To a large extent, hydrogen could be a way to help manage the intermittent nature of renewable electricity. The cost is a low energy yield as the round-trip electricity-to-hydrogen-to-electricity means an overall efficiency in a 25%-40% range.[40]

[37] FAQs: Green Steel - SSAB
[38] Decarbonisation in Hamilton, Canada, ArcelorMittal 2021
[39] SSAB plans a new Nordic production system and to bring forward the green transition - SSAB
[40] "Making the Hydrogen Economy Possible", Energy Transitions Commission, 2021

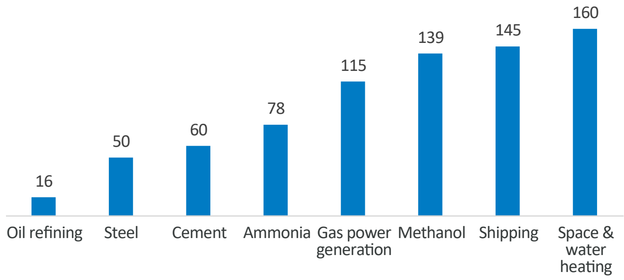
Cost of hydrogen and cost of CO_2

As in any discussion on the energy transition, the question of introducing a cost of CO_2 is part of the hydrogen debate. The cost elements highlighted above would be largely unchanged for green hydrogen if a CO_2 cost was charged for carbon emissions.[41] This would however increase the cost of all fossil fuel-based products, including grey hydrogen. This would, as a result, positively improve the relative competitiveness of hydrogen and its derivatives.

The chart opposite shows the estimated required cost of one tonne of CO_2 for hydrogen to be competitive relative to fossil fuels for several industrial applications, assuming a \$1/kg green hydrogen cost in 2050.

A cost of carbon is an important step for hydrogen to be viable outside of a few core end-uses where it is the best lever to decarbonise. This chart shows that the current price of CO_2, at least in some regions, is high enough for hydrogen to be in the minds of relevant corporate executives.

Carbon price (in \$) required for hydrogen to be competitive



Source: "Making the Hydrogen Economy Possible", Energy Transitions Commission, 2021

Hydrogen, politics, and sovereignty

Green hydrogen can be produced almost anywhere. As long as there is some wind and sun and access to water, it can be technically produced. This is a sharp contrast with fossil fuels where geology is the driving force. An oil field cannot be delocalised.

This does not mean that it makes economic sense to produce green hydrogen everywhere, but it changes the thinking about energy sovereignty. Renewable electricity allows us to reduce our dependence on fossil fuels, even more so with the addition of hydrogen. This can lead to strategic decisions where the economic equation is secondary to sovereignty and security issues.

However, wind and solar resources are not evenly spread. Some regions – such as Chile, the North Sea, the Middle East or Australia – have better conditions to develop green electricity. Translating this into the hydrogen value chain, this could create hubs where green hydrogen is produced with a superior cost structure and then shipped, most likely as hydrogen if pipelines are an option or as ammonia if being shipped. It is not far-fetched to envisage global trade routes similar to that which exists today for liquefied natural gas.

Natural gas companies could also attempt to reinvent themselves as blue hydrogen companies, converting their methane into hydrogen and utilising retrofitted gas pipelines.

Many countries – and regional organisations such as the European Union – have announced hydrogen strategies. Beyond the goal of reducing carbon emissions and generating economic growth, they pursue broader goals of energy security. This has been reinforced in recent years by the supply chain disruption caused by COVID-19, and more recently by the war in Ukraine.

[41] Green hydrogen is CO_2 free, although there could be CO_2 costs incurred in its value chain

A place at the table?

Climate change has become the long-term focus of the world's attention, and carbon has become a dirty word. Our analysis leads us to believe that hydrogen's moment appears to be coming – and with the evidence and momentum this time around to give it a genuine place at the table in the energy transition. It will not be as widely used as its most enthusiastic eulogists predict – notably its role in passenger cars is doubtful, in our view – but its credentials to decarbonise heavy-duty transportation and industrial processes are convincing to us.

Costs must fall, however, and most notably progress is needed in the capital intensity and cost of renewable power. Also, carbon must have a consistent, agreed price for green hydrogen to really become a no-brainer for businesses seeking energy solutions.

We would argue that investors should very carefully assess the opportunities and risks of the hydrogen space.

We believe that renewable electricity is a clear and obvious way to be exposed to the growth of green hydrogen. A higher use of electricity and the electrification of many processes promise decades of developments for solar and wind power. While we acknowledge that green hydrogen is one amongst those many growth avenues, it also means that risks are spread. Electric utilities with strong credentials in renewables ought to benefit from the rise of the hydrogen economy.

We have seen that hydrogen is not an easy molecule to handle. As such, we believe that companies already active in the production and especially the logistics of hydrogen – namely industrial gas producers – have a competitive advantage. Their know-how in managing a complex value chain sets them ahead of would-be competitors. A few mostly Western integrated oil and gas companies have started to invest in hydrogen. Their experience in complex energy value chains and chemical processes could make them credible hydrogen players, although they will primarily remain fossil fuel producers for many years.

Equipment providers are an area where risks may win over opportunities. Most notably, producers of electrolysis technologies are likely to see very strong volume growth, but also strong price pressure and sharp competition. We expect in time to see commoditisation arising for those selling the picks and shovels of the green hydrogen industry.

Recommended reading:

- "Making the Hydrogen Economy Possible", Energy Transitions Commission, April 2021
- Hydrogen Insights 2021, Hydrogen Council, July 2021
- Global Hydrogen Review, IEA, October 2021
- Green hydrogen cost reduction, IRENA, December 2020