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Hydrogen handbook

2025

HydrogenOne Capital LLP is a specialist investment manager in the clean hydrogen market.

Our “handbook” is a starter pack for this quite complex and rapidly-growing sector.

Post-COVID exuberance in energy transition investment has been tempered by inflation and politics. Yet the realities of climate change, and hydrogen’s key role in decarbonisation continue to drive the sector.

Some 0.2mtpa of clean hydrogen is in production today, just a fraction of the 97mtpa polluting grey hydrogen market. This should rise to 3mtpa by 2027, as the sector continues to grow, abating 29mtpa of CO_2, backed by c.$69 billion of investment.

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Executive summary

Structural drivers…

- Climate change, air quality and energy security. The three big drivers of the clean hydrogen theme
- Today's 'grey' hydrogen sector is a 97mtpa, $175bn/year market that emits 830mtpa of CO_2. Cleaning this up is the major demand pull for clean hydrogen today
- Hydrogen can be used more broadly in today's fossil fuel system, especially to move heavy objects like ships, trains, HGV, and power generation
- Clean hydrogen is a solution for large scale storage and shipping of renewable power, using salt caverns, natural gas grid blending, dedicated hydrogen pipelines and tanks, addressing grid balancing and energy security
- Clean hydrogen is a key component in the manufacture of clean e-fuels, such as e-methanol and synthetic aviation fuel ("SAF"), and green ammonia

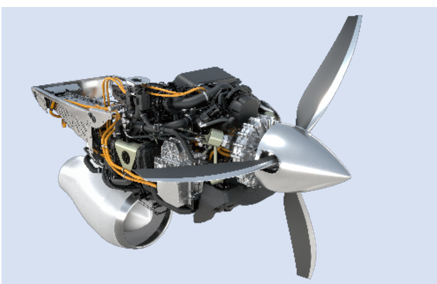
Near-term trends…

- Post-COVID optimism for energy transition has been buffeted by supply chain shortages, inflation, high interest rates, and the Russia-Ukraine war
- Renewables investors unsettled by the sharp reversal of energy transition strategy in the USA, and the delays in policy implementation in Europe and the UK
- UK oil companies have reverted to oil & gas activities. Yet Big Oil is investing in blue and green hydrogen, adjacent to its refinery and CCS footprint, for internal consumption.
- A 'chicken-egg' has developed where hydrogen off-takers are slow to sign the long-term offtake agreements that are needed for bankable finance, until country level regulations and GHG penalties are in place
- Nevertheless, the sector is gathering pace: 3mtpa green hydrogen is now post-FID, a 15X increase in supply, double our projections from a year-ago, and c. $69 billion of investment committed. Industrial gas, buses, stationary power and e-fuels are the most advanced themes

Portfolio company

Sunfire GmbH

German industrial electrolyser producer, of pressure alkaline (AEL) and solid oxide electrolysers (SOEC)



Portfolio company

Cranfield Aerospace

UK-based passenger flight innovator, powering turboprop flight with hydrogen

Portfolio company

HiiROC Limited

UK-based thermal plasma electrolysis developer, with world-leading (IP-protected) technology

HydrogenOne

HydrogenOne Capital LLP is a specialist investment manager in clean hydrogen.

Our "handbook" is a starter pack to understand the background and emerging trends in this complex and rapidly-growing sector.

Post-COVID exuberance in energy transition investment has been tempered by inflation and politics. Yet the realities of climate change, and hydrogen's key role in decarbonisation continue to drive the sector.

Some 0.2mtpa of clean hydrogen is in production today, just a fraction of the 97mtpa polluting grey hydrogen market. This should rise to 3mtpa by 2027, as the sector continues to grow, abating 29mtpa of CO_2, backed by c. $69 billion of investment.

Market development

As markets came out of COVID lockdowns in 2020-2021, there was strong investor and societal appetite for cleaner, healthier lifestyles and acceleration of the energy transition. Since then, many growth sectors have been buffeted by supply chain shortages, inflation, high interest rates, and the Russia-Ukraine war.

In addition, renewables investors have been unsettled by the sharp reversal of energy transition strategy in the USA, push-back on ESG themes, and the delays in policy implementation in Europe and the UK, where for example there is slow country-level uptake of RED III, and a roll back of ICE phase out in the transport sector.

The fossil fuel companies, especially in the UK, have reverted to oil & gas activities, under pressure from shareholders (who had pushed them into energy transition in the first place), and are significantly slowing down their renewables activities. Big Oil essentially is investing in blue and green hydrogen, adjacent to its refinery and CCS footprint, for internal consumption.

In terms of green hydrogen projects, a 'chicken-egg' has developed where off-takers are reluctant to sign the long-term offtake agreements that are needed for bankable finance, until country level regulations and GHG penalties are in place. This has resulted in a series of project cancellations and delays, which has flowed through into the order books of listed electrolyser and fuel cell companies, and selling pressure on share prices.

That said, we are tracking **strong progress in clean hydrogen**, which is deploying in different market segments and geographies at different rates, depending on fiscal support, customer demand, electricity prices and grid development.

By 2027, some 3.0 mtpa of green hydrogen is expected to be in production globally, following investment of some $69 billion, representing a c.15x increase compared to the current green hydrogen market, and predominately used to replace grey hydrogen. This growth is made up of 389 projects, with an average size of 59MW (8 ktpa). These are real projects, past FID and financial close, with construction underway. Demand for this hydrogen is underpinned by refineries and chemicals plants, with additional offtake for transport fleets.

In addition, we are tracking a further 44 mtpa of green hydrogen projects that are under development, meaning FEED, land purchase, long lead items purchase, ahead of FID.

In the **heavy transport sector**, we are seeing steady roll out of hydrogen buses, with city fleets in Europe, South Korea and some parts of North America. Solaris, for example, has delivered over 400 hydrogen buses and has another over 400 in its order book. Wrightbus has delivered c.170 hydrogen buses and will make over 100 more this year, with EU legislation requiring fossil phase out 2030-35. Hydrogen-powered HGV is a longer-term trend, reflecting back-ended GHG regulations, with multiple OEMs trialing fuel cell and hydrogen combustion HGV and building out hydrogen refuelling, in particular in the EU, China South Korea and Japan in particular. Hydrogen in **light transport** needs to compete with battery EV, which is currently winning in this market.

Salt caverns are emerging as a large-scale hydrogen storage and grid balancing tool for intermittent renewable power. The ACES project, under construction in Utah, will have 220MW of electrolysis and 9 million boe of salt cavern hydrogen storage coming on line in 2025. In Germany, the Bad Lauchstädt Energy Park has a 30MW electrolyser and slat cavern storage. Developer companies, especially in the UK, EU and USA are earmarking salt geology for the roll out of large-scale hydrogen storage.

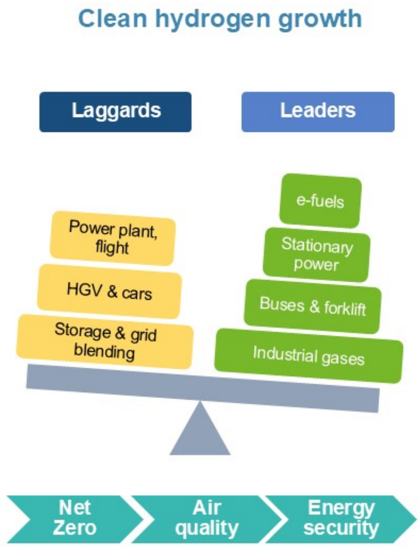
In **power generation**, burning hydrogen as an alternative to natural gas in turbines is not new. GE, for example, has older units with more than 100,000 hours working with hydrogen fuels. Siemens Energy has been using hydrogen in various applications for over four decades. Recent co-firing tests in US power plants have demonstrated the technology for burning natural gas with up to 44% hydrogen blend. The biggest obstacles to hydrogen firing in gas turbines are less technical and have more to do with the challenges of building new infrastructure and ramping up hydrogen supply. Off grid, **stationary power** is a sector to watch. This is a fuel cell-based technology that can use grid gas, biogas, ammonia and hydrogen as an input, to make electricity in settings where there is a lack of grid capacity, for example in EV charging sites, marine or construction.

Hydrogen can be safely **blended with natural gas**, in existing or modified natural gas networks. This has the advantages of a built-in market for hydrogen and getting it to customers, without rebuilding the energy system along the way. Typically, 1% blends are permitted in many countries. The UK, Germany, Italy, New Zealand, and others all working to inject a higher percentage of hydrogen into gas networks (up to 20%), while ensuring the integrity of existing infrastructure and appliances is not compromised. These proposals are resisted by natural gas and biogas suppliers, and hence progress has been slow.

In **flight,** there are multiple pathways to decarbonization that involve hydrogen, such as battery electric with fuel cell in turboprop, SAF and hydrogen turbine. These are all in innovation / R&D, and are early stage.

Market development

- Post-COVID optimism for energy transition buffeted by supply chain shortages, inflation, high interest rates, and the Russia-Ukraine war
- Renewables investors unsettled by the sharp reversal of energy transition strategy in the USA, and the delays in policy implementation in Europe & UK
- UK oil companies have reverted to oil & gas activities, but investing in blue and green hydrogen, adjacent to refinery and CCS footprint
- A 'chicken-egg' has developed where hydrogen off-takers are slow to sign bankable offtake agreements until country level regulations are in place
- Despite this, the sector continues to gathering pace: 3mtpa green hydrogen is now post-FID, a 15X increase in supply for 2027



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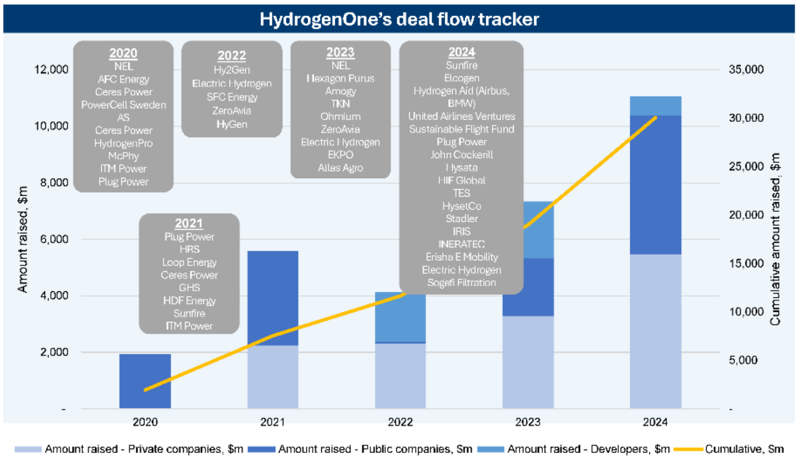
Strong increase in investment in clean hydrogen in 2024



OMV Petrom investing c. €190m in 8ktpa green hydrogen at Petrobrazi for production of sustainable fuels

A total of $11 billion (c. £9 billion) of new investment has been committed into clean hydrogen companies in 2024 (+60% vs FY 2023)

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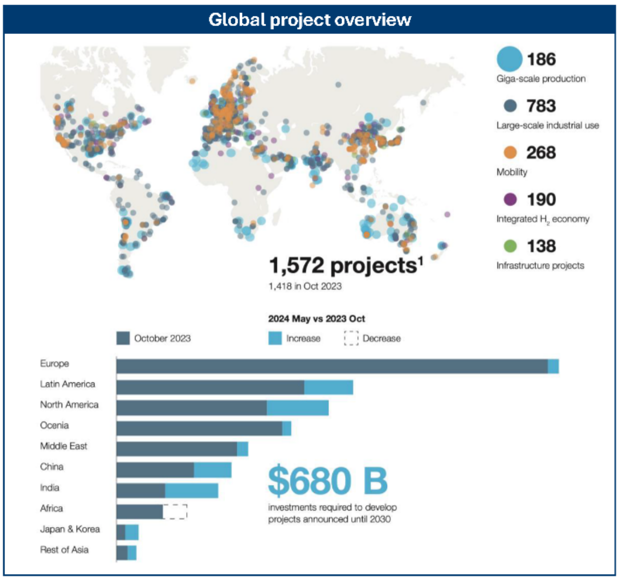
Hydrogen Council view of project landscape



- 1,572 projects announced globally – $680 billion investments announced through 2030 (+10% vs 2023)
- Giga-scale projects account for more than half at over $380 billion.
- Europe continues to have the largest number of projects (617), followed by North America (280)
- Europe also has the highest total investments announced ($199 billion).
- Japan and South Korea show the highest relative growth in investments vs 2023 +130%, India +110%, followed by Rest of Asia with 75% growth.

https://hydrogencouncil.com/wp-content/uploads/2024/09/Hydrogen-Insights-2024.pdf

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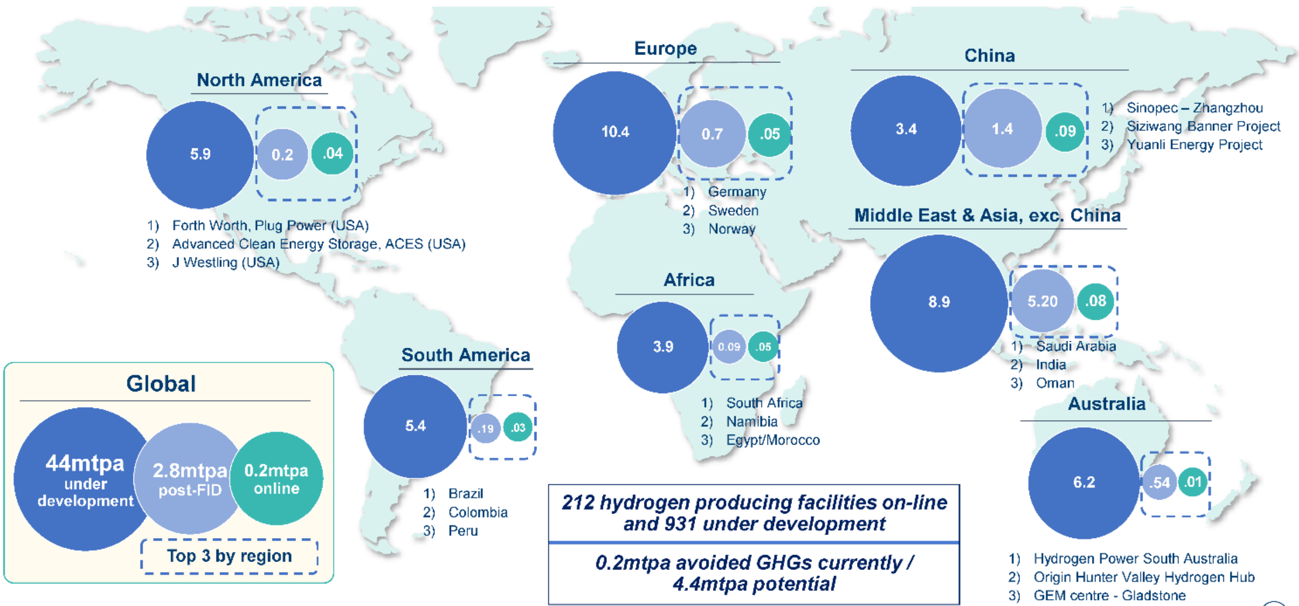
Green hydrogen capacity +25% 2024



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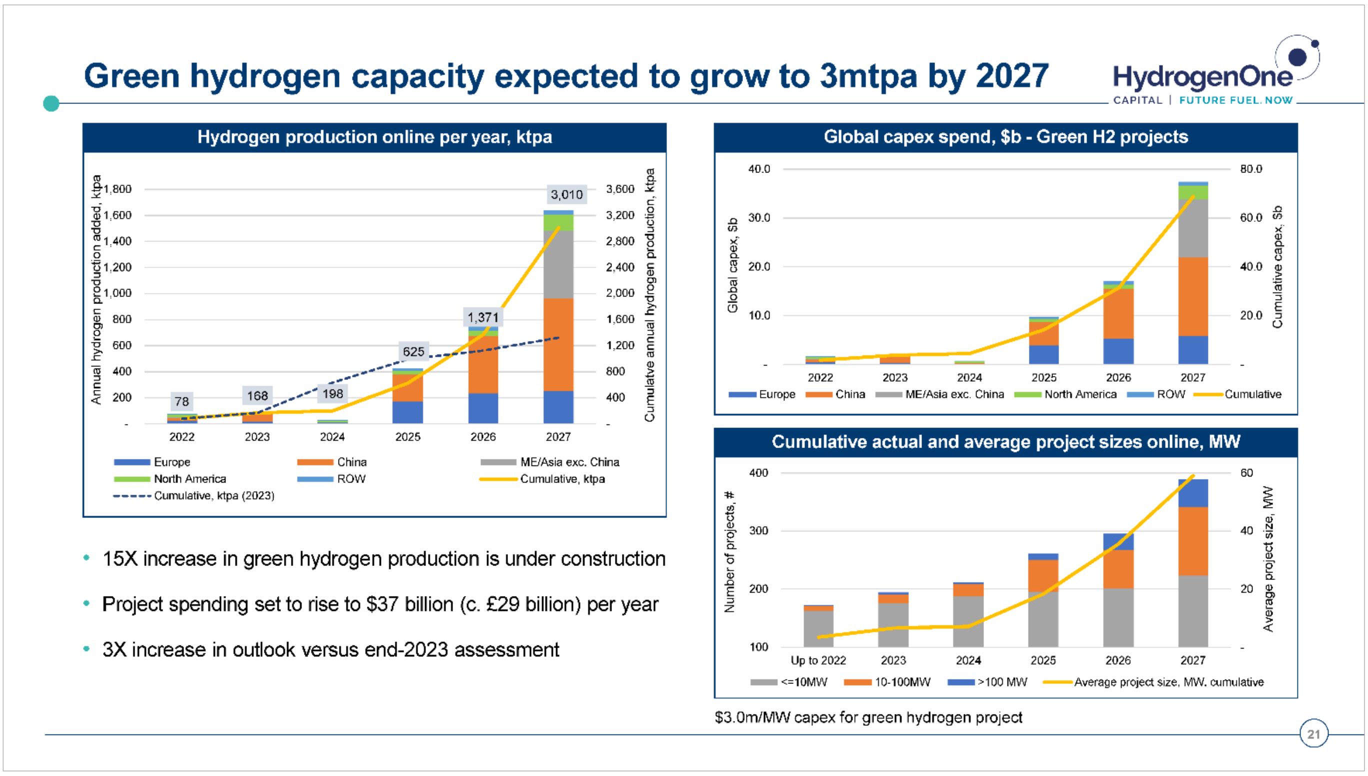


Hydrogen – the basics

The hydrogen market today is large and well established, at some 97 million tonnes per year, $175 billion of annual revenues, and dominated by industrial gas companies.

Almost all of the hydrogen in use today (over 95%) is made by splitting coal, oil and natural gas, and releasing the resulting GHGs to the atmosphere. This hydrogen, known variously as “grey” or sometimes “black” results in over 800 mtpa of GHG emissions and is a major polluter.

This grey hydrogen is widely used as a gas as a feedstock for ammonia and oil refining, mainly as a desulphurization agent and as a reducing agent in the steel and cement industries. It is also used as a coolant in the power sector. Hence much of the activity in “**clean hydrogen**” is about replacing grey hydrogen with **clean hydrogen** in heavy industry settings, which is a $175 billion/year opportunity for clean hydrogen investors.

Clean hydrogen can be made in several ways, which are colour coded. There are four basic types, and others in the R&D stage.

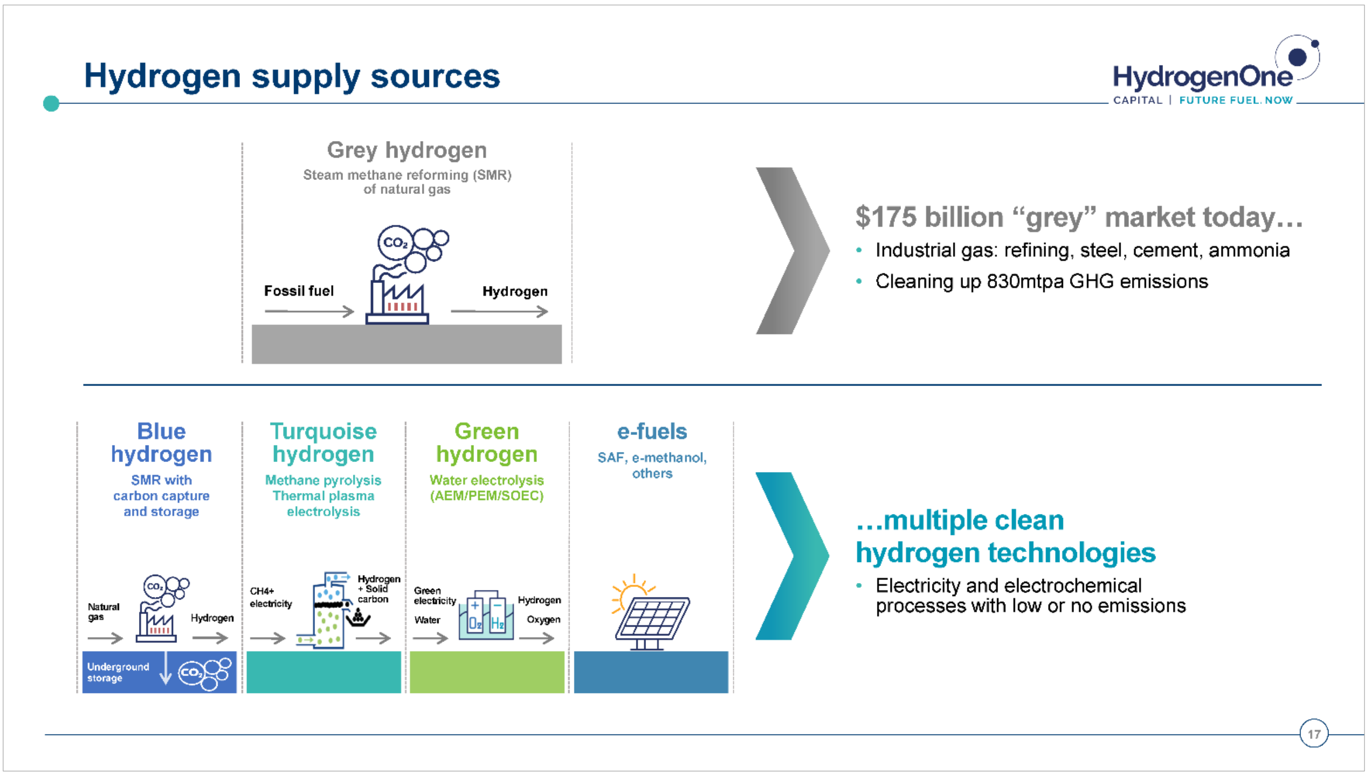
Grey hydrogen is how we make it today. By heating methane gas with steam, a process called steam methane reforming – (“SMR”). This is efficient but releases CO_2. This is a large industry today and has been around for decades.

Blue hydrogen uses SMR, like grey, but captures the CO_2 and stores it in geological reservoirs (CCS or CCUS).

Green does not involve hydrocarbons, and uses renewable electricity – e.g. wind and solar – to run electrolysers, which make hydrogen and O_2 by splitting water.

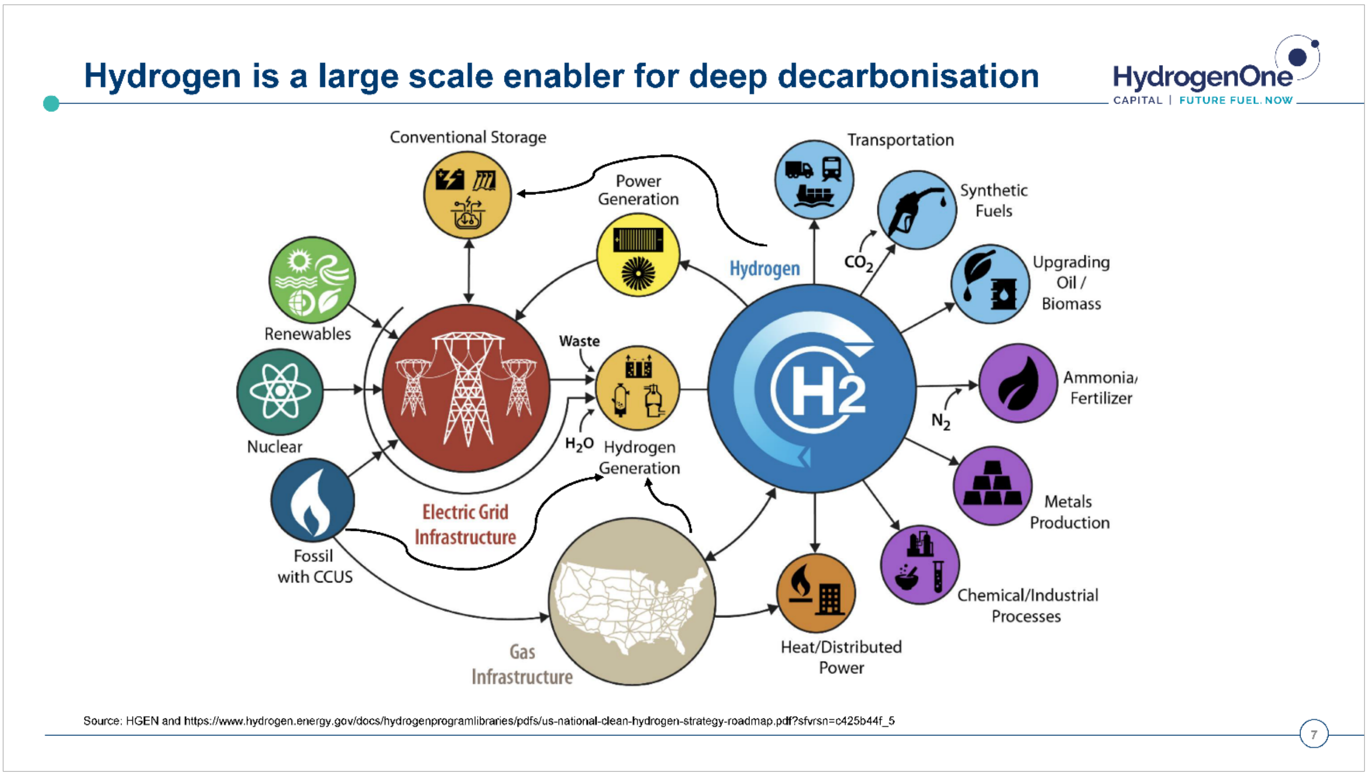
Turquoise hydrogen is a pyrolysis treatment, which results in the chemical decomposition of conventional natural gas, which produces hydrogen and solid carbon as a by-product.

There are other forms of clean hydrogen, such as white and gold, which are at the innovation/R&D stage.



The prospect of manufacturing clean hydrogen – with little or no GHG emissions – is enormously attractive to the industries that use grey hydrogen today – they are under substantial pressure to clean up, to play their part in Net Zero, and avoid the penalties and fines that are being applied by governments to drive to net zero. The large majority of demand for clean hydrogen today comes from these polluting incumbent industries.

But there is a bigger picture. The energy system is being electrified to replace fossil fuels, in order to mitigate climate change. In that, clean hydrogen is set for a pivotal 'enabler' role, sitting alongside the electricity grid as a customer and storage medium for surplus power, a fuel in power generation and gas grids, an energy carrier that can be converted back to electricity with fuel cells, and a feedstock for traditional industries and e-fuels.



What drives demand for clean hydrogen?

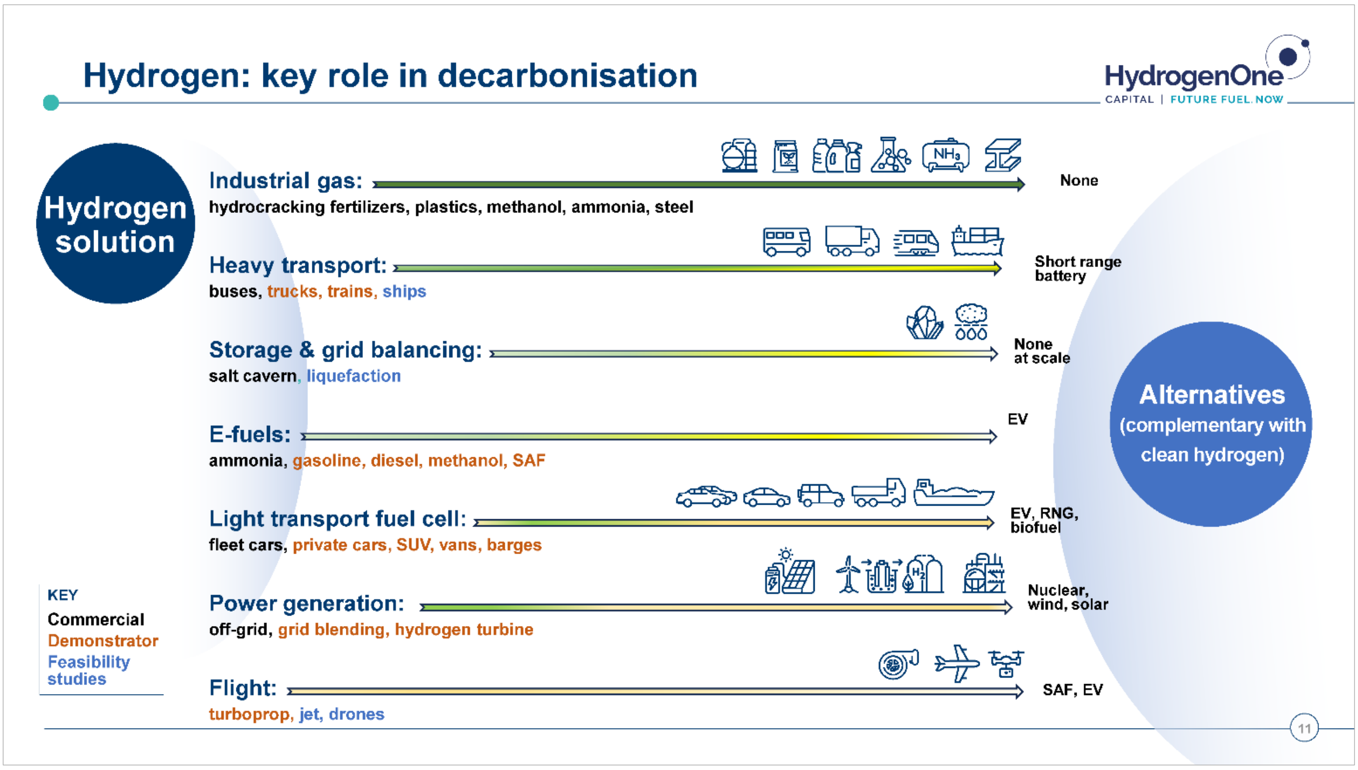
Over 75 governments have set net zero strategies that include clean hydrogen, with grants and funding as incentives totalling $100 billion in 2024, and fines and penalties to incentivise uptake.

Some 97 million tonnes per annum (“mtpa”) of hydrogen is used today in **oil refining**, chemicals and steel. The demand to replace this polluting ‘grey’ hydrogen with clean hydrogen underpins the sector and accounts for virtually all of the clean hydrogen demand today.

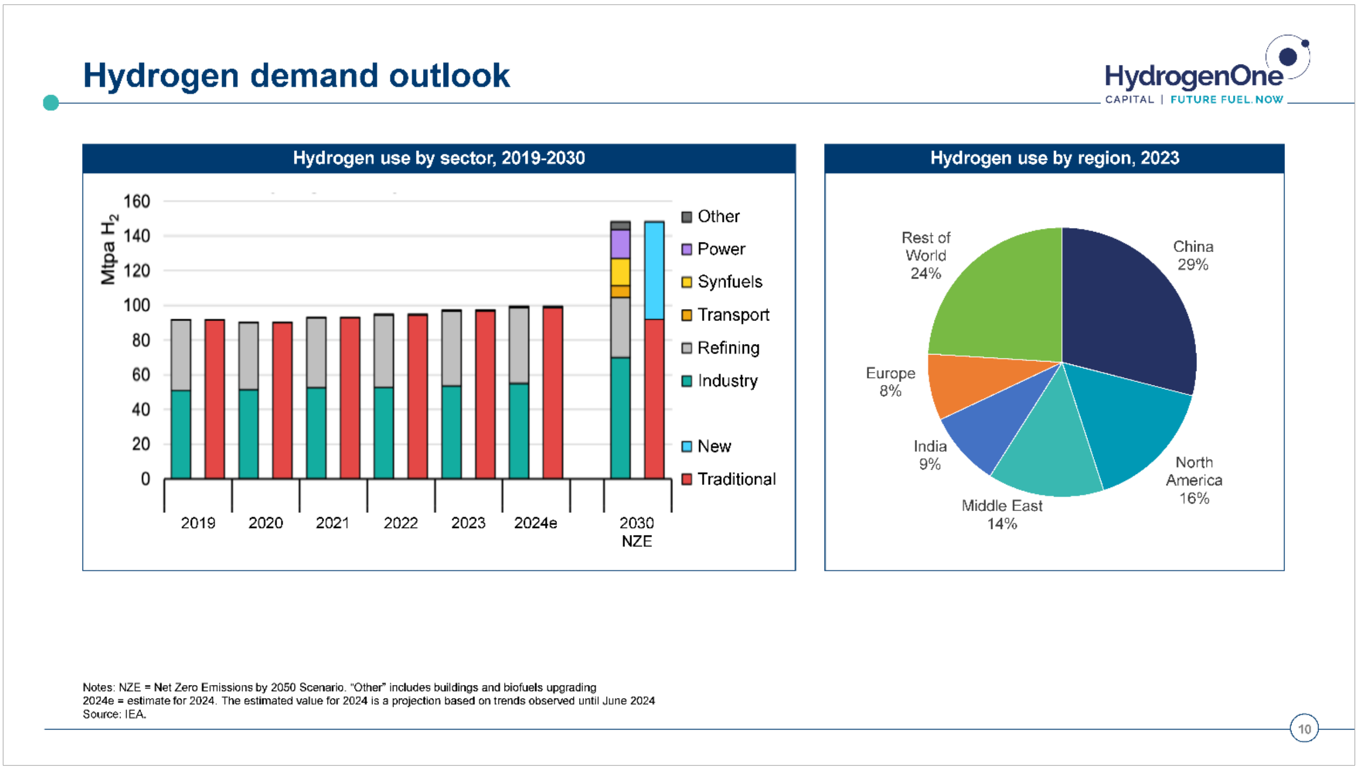
Hydrogen and battery electric (“EV”) are complementary technologies in **heavy transport**, where access to electricity recharging and hydrogen, and range requirements are shaping demand.

Governments are also focused on **storage, grid balancing and energy security** considerations. Clean hydrogen is an energy carrier, that can store and distribute intermittent renewable electricity at a large scale, in salt caverns and blending in natural gas grids. Hydrogen combined with renewables such as wind and solar provides a domestic energy supply option for many countries, reducing reliance on imported energy and improving energy security.

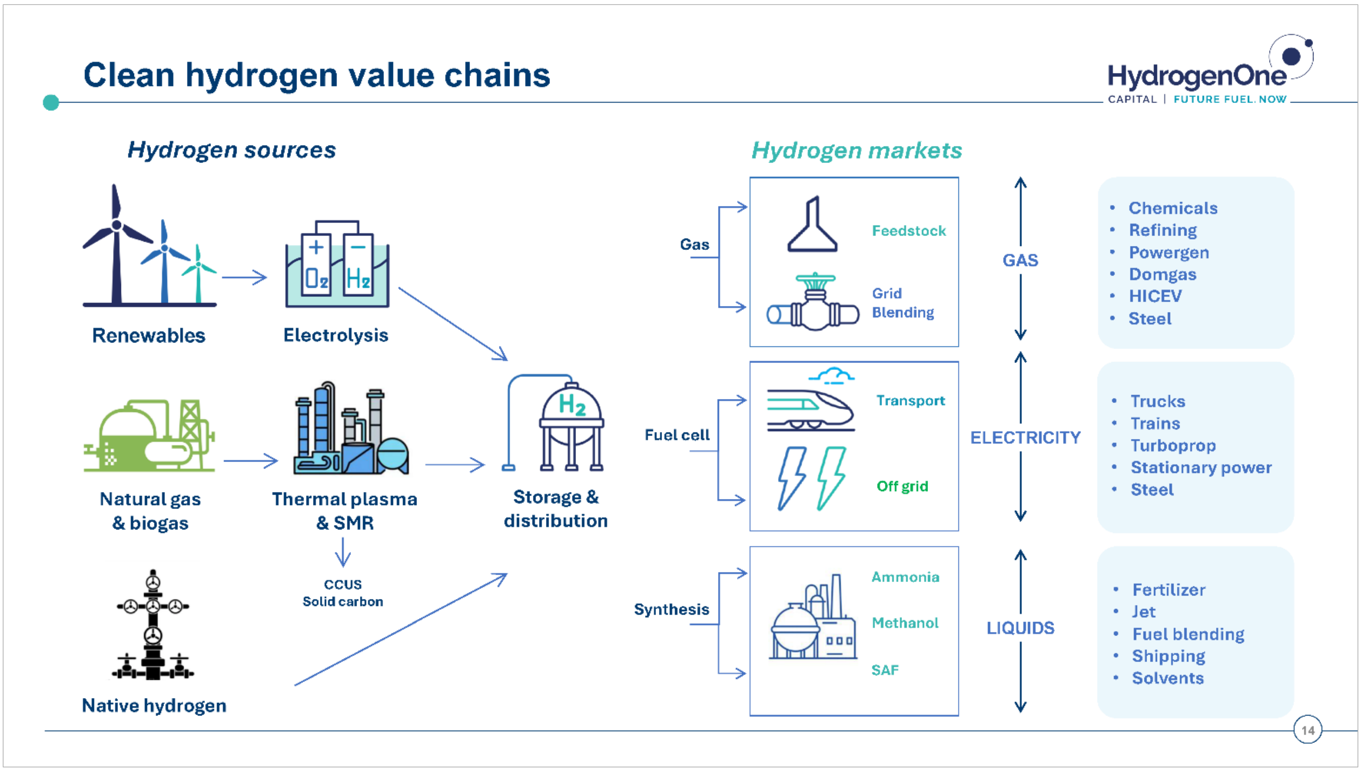
Clean hydrogen can replace fossil fuels in hard to decarbonise sectors such as **power generation** and **light transport**, although EV is a more likely winner there. Clean hydrogen is a key component in the manufacture of clean e-fuels, such as e**-methanol and synthetic aviation fuel** (“SAF”).



By 2030, some 35% of the hydrogen market could be clean, and 25% of the consumption in themes traditionally the preserve of the fossil fuel industry.



What are the key components of the clean hydrogen industry?



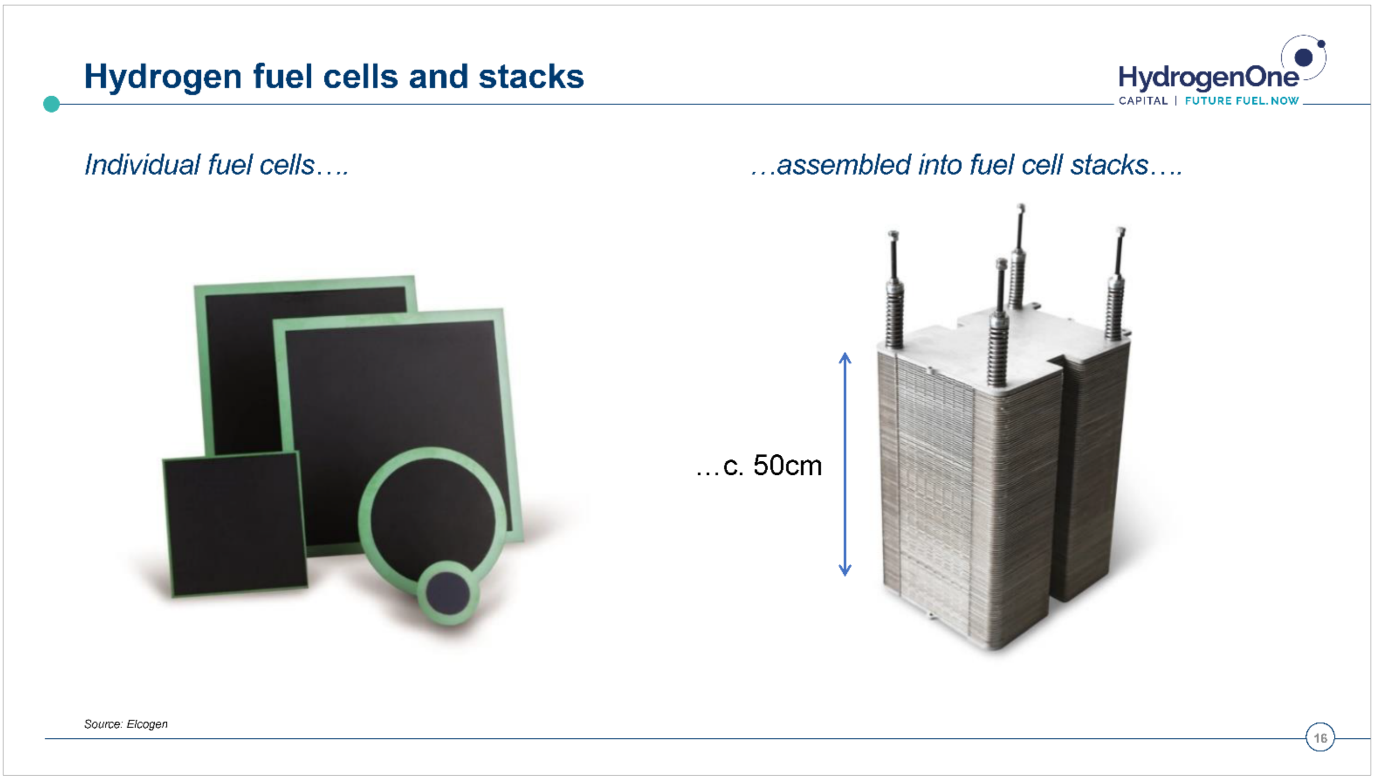
Clean hydrogen is made at industrial sites with access to low-cost green electricity ("green") or natural gas and geological CO_2 storage sites ("blue").

If you know the renewable power and natural gas industries, then green hydrogen is familiar ground. Dedicated wind, hydro or solar power, or a renewable PPA, provide electricity that powers electrolysers, which make hydrogen. This is compressed and sold to off-takers, typical in industry and transport. The off-taker provides a Hydrogen Sales Agreement ("HSA"), which underpins the financing for the infrastructure.

The hydrogen is **shipped or stored** in pipelines and tanks to customers. For industries such as oil refining, hydrogen is used in the desulphurization of crude oil, amongst other processes. Alternatively, fuel cells are used to convert the hydrogen to electricity or heat – this can take place in trucks, trains and buses via hydrogen tanks, or in large buildings such as hotels and offices, using combined heat and power ("CHP") units.

Hydrogen has a similar *energy mass* (energy per kilogramme) as conventional liquid fuels such as gasoline. However, hydrogen has a lower *volumetric energy density*, and the gas is compressed and stored in pressurised tanks for storage and shipment. Some participants are planning to ship large volumes of liquid hydrogen from supply sources to customers, or to transport hydrogen by first converting it to liquid ammonia. Liquid hydrogen storage needs cryogenic tanks maintained at -253°C. Ammonia has a high hydrogen content (17.65 wt per cent.), it has an established distribution network, and the ability to be liquefied at 10 bar or -33°C.

Electrolysers are the key component of green hydrogen supply. These car-sized units use electricity to split water into O_2 and hydrogen. Companies such as ITM Power in the UK, and Siemens Energy in Germany are major electrolyser suppliers. INEOS is currently Europe's largest electrolyser technology operator, with 400,000 tonnes per annum of hydrogen production.



Once produced, hydrogen has to be transported and stored. There is an established manufacturing industry that is adapting to the new specifications required for hydrogen gas. These businesses supply compression, pipelines, storage cylinders and tanks.

Over time, **Hydrogen Refuelling Stations ("HRS")** are expected to move from specialized truck, bus and train depots to mainstream petrol station forecourts. Other applications include the decarbonization of portable power from diesel- and petrol-powered generators to hydrogen powered units.

Fuel cells, which are brick-sized to cooker-sized units, convert hydrogen to electricity with water as a by-product. Fuel cells can also use methane and ammonia as an input to create electricity.

Government policies

Some 75 countries and territories have policies in place to support growth in the clean hydrogen industry. Many countries have policies, targets and funding in place to put hydrogen into the transport sector for Net Zero and air quality. Globally some $100 billion of public funding was announced in the industry in 2024 alone to underpin this.

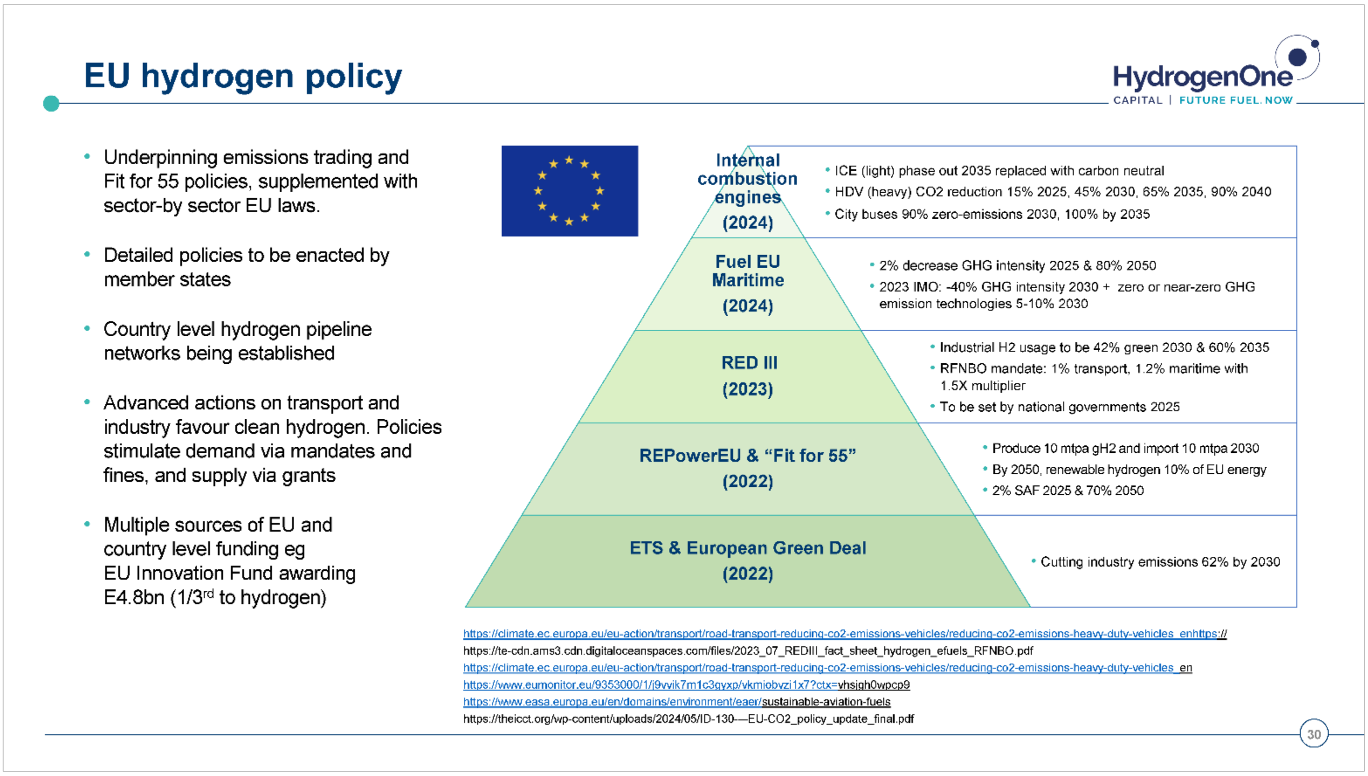
Yet Government policies and funding are moving at different rates around the world, as is the case for most renewables technologies. The EU seems the most advance currently, with slower progress in the UK after the 2024 election, and the USA essentially in limbo at the time of writing.

The **EU is amongst the most advanced regions in terms of hydrogen policy formation**, and is seeing substantial investment as a result. 2020 saw EU targets for hydrogen to meet 14% of Europe's energy needs by 2050. In 2022, the EU reshaped its energy policy to the REPowerEU 2030 plan, which calls for over 300GW of clean hydrogen by 2030, compared to 80GW in previous plans. Some €5.4 billion in hydrogen subsidies have recently been approved under Important Projects of Common European Interest ("IPCEI"), which are expected to unlock a further €8.8 billion of private investment.

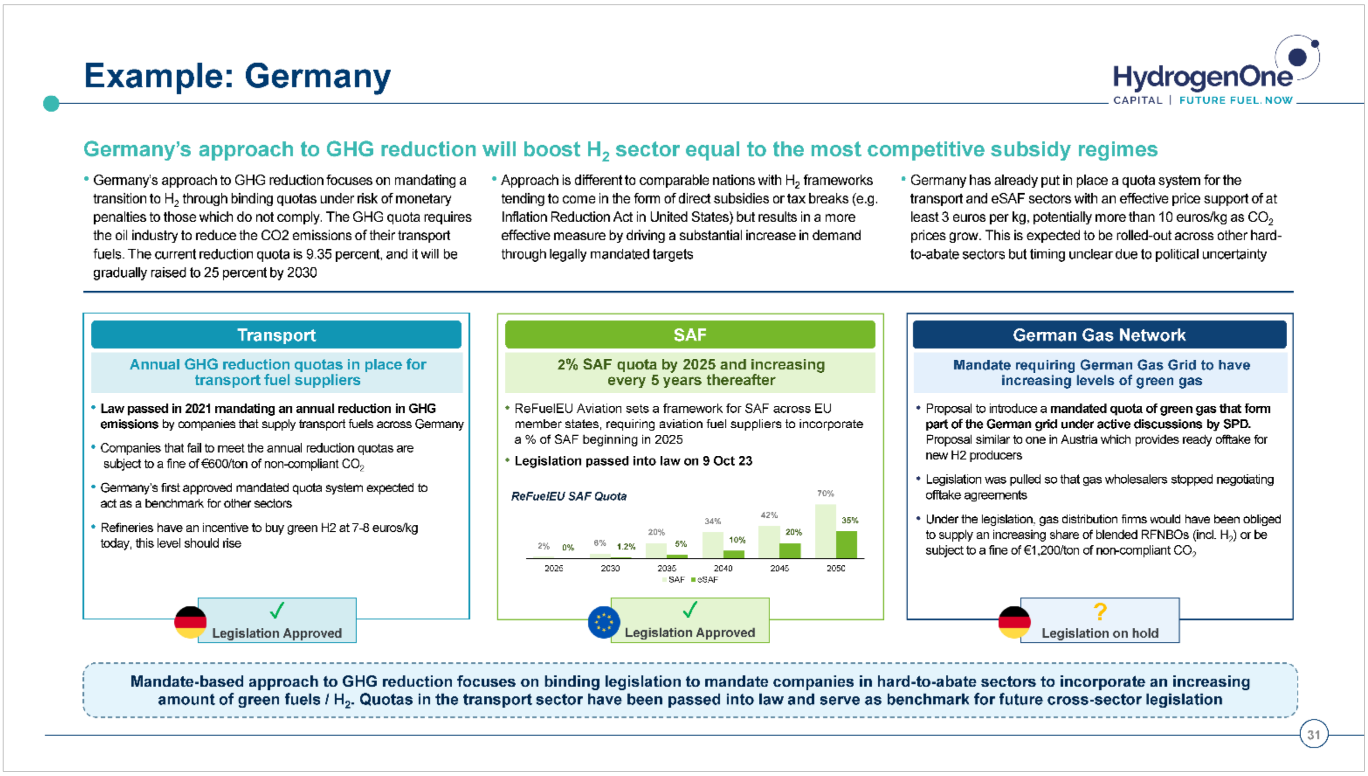
The Hy2Tech scheme, also announced in 2022, links 41 projects and 35 companies building out the hydrogen sector, and has qualified for IPCEI funding. The EU's Hydrogen Bank auctioned €720m of opex subsidy to green hydrogen in 2024 and will auction a further €1.2 billion in 2025.

There are additional sources of grant funding at a country level in multiple EU countries. Importantly, RED III legislation has been put into EU law, and is due for country level implementation in 2025. RED III calls for industrial H2 usage to be 42% green by 2030, and 60% by 2035. The rules also include mandates for Renewable Fuels of Non Biological Origin (RFNBO) of 1% in transport and 1.2% maritime with 1.5X multiplier.

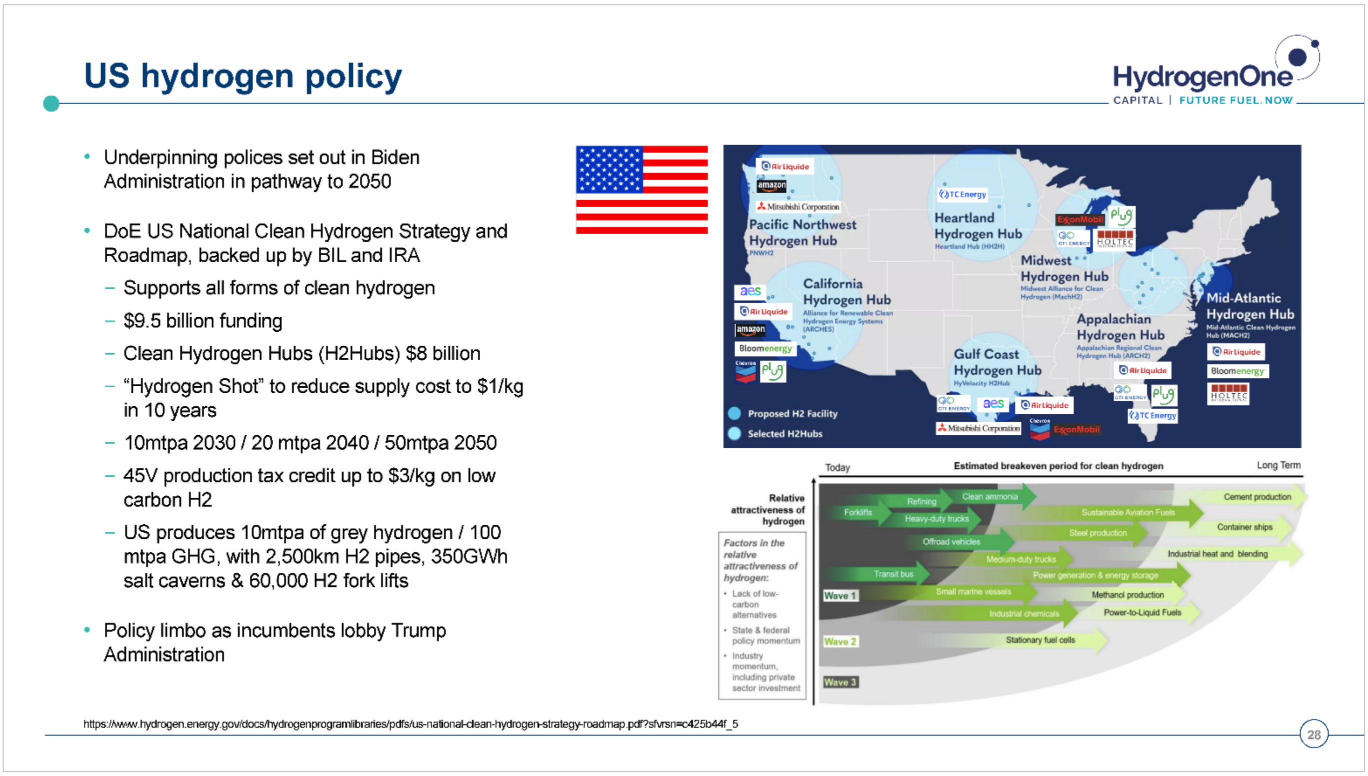
In the transport sector, there are planned phase outs of fossil fuels in flight, shipping, cars, buses and HDV, which are impacting investment decisions from customers and OEMs today.



Country-level adoption of the EU regulations sees **Germany** in particular advancing with a hydrogen pipeline network to enable the sector, connecting its industrial heartlands, with government backing of over €20 billion. **Spain** has recently selected 16 projects for its €1.2 billion hydrogen valley programme, with major companies Repsol, Moeve and bp among the beneficiaries, and ambitions to dominate the regional market. The **Finnish** Government plans to become world leader in hydrogen, aiming to produce 3 million tons of hydrogen annually by 2035, which is expected to generate €33 billion in government revenue. By 2030, the Nordic nation plans to produce over 14% of the EU's green hydrogen, and this is expected to create over 115,000 new jobs in 2035.

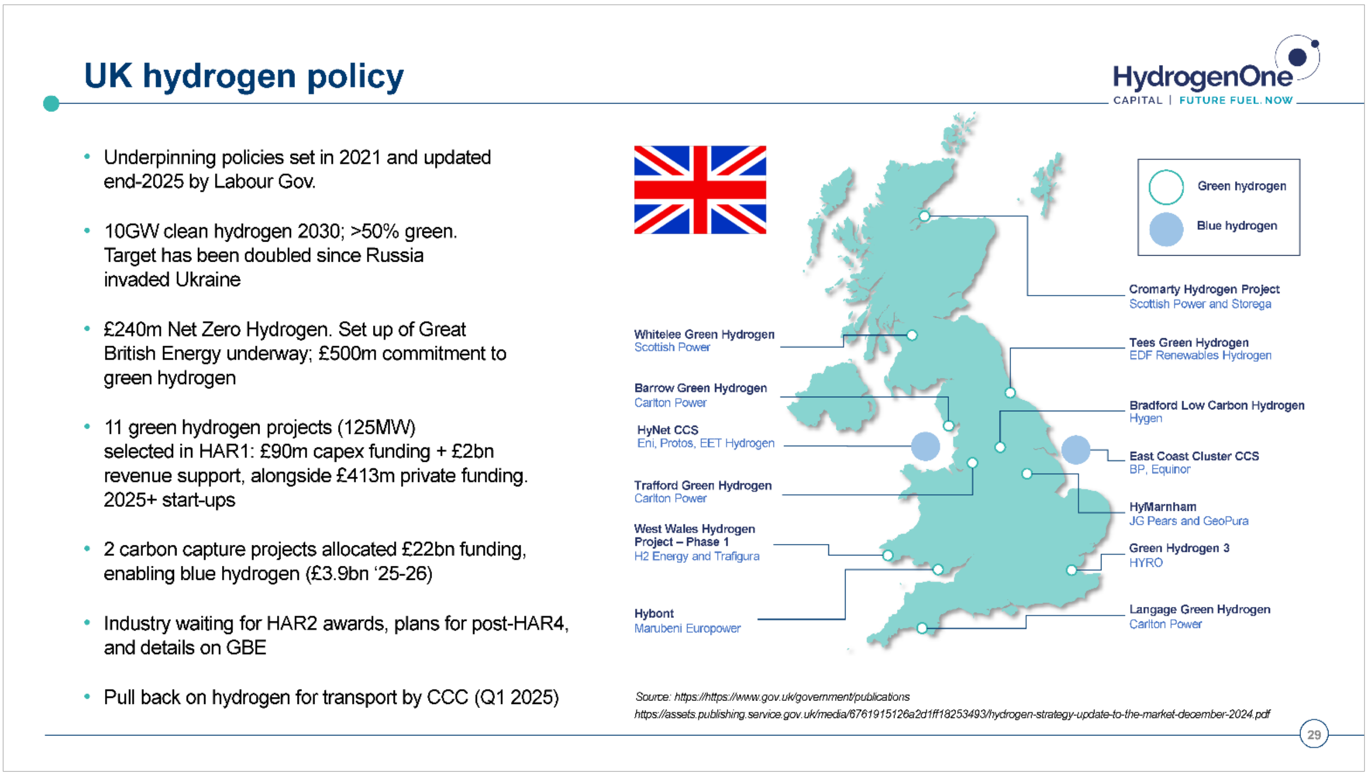


The **United States was set to be the global leader in energy transition** adoption under the Biden-era Inflation Reduction Act, which was strongly supportive of clean hydrogen. The Department of Energy had, under President Biden announced a US$8 billion programme to develop clean regional hydrogen hubs across the country, as part of net zero ambitions by 2050. The 2022 Inflation Reduction Act set aside US$369 billion for climate and energy proposals. Within this Act, there is a tax credit for clean hydrogen of US$0.6/kg to US$3/kg, depending on life cycle emissions. This was expected to make green hydrogen cost competitive with grey hydrogen, and make US clean hydrogen amongst the lowest cost in the world. At time of writing, this policy is essentially on hold, pending President Trump's plans for renewables.



In **India**, in early 2023, the Government announced the Strategic Interventions for Green Hydrogen Transition Programme ("SIGHT"). This programme envisages c.$100 billion of investment to 2030, 60-100GW of electrolyser capacity, resulting in 5 million tonnes per annum of green hydrogen production. This is initially planned to address GHG emissions from the fertiliser, refining and iron and steel sectors, by replacing grey hydrogen there.

In the **UK**, **the Johnson Government had set ambitious targets t**o deliver clean energy and hydrogen by 2030, including plans to deliver 10GW of low-carbon hydrogen by 2030. The current UK Government has yet to set out its plans for the hydrogen sector. However eleven green hydrogen projects were selected in the HAR1 round, at the end of 2023, and received 2024 funding for £90m of capex funding and £2 billion of revenue support. The new (2024) government has pledged to allocate £500 million in financial support for green hydrogen producers, as well as £22 billion for CCS infrastructure critical for the development of the blue hydrogen sector. This would be supported by a proposed £8.3 billion Great British Energy and financed by a £7.3 billion National Wealth Fund, which would also allocate £2.5 billion to supporting the UK's steel sector, potentially favourably impacting investment in green hydrogen-derived steel. The UK Government's Climate Change Committee has recently determined that the transport sector will be predominantly EV, rather than a combination of EV, CNG and hydrogen.



In **Denmark**, an ambitious Hydrogen and Power-to-X strategy was announced in March 2022, calling for 4GW to 6GW of installed hydrogen electrolysis by 2030, using wind and solar power, putting DKK 1.25 billion of subsidy funding in place, and the policy and regulatory frameworks that are required for this.

As a further example, in 2019 the **Netherlands** set targets for 3GW to 4GW of electrolysis by 2030 with multi-billion- euro funding support announced by the Netherlands government. The government is providing €750 million of funding support for a "hydrogen backbone", retrofitting existing natural gas pipelines to transport hydrogen between five industrial clusters in the Netherlands, and at cross-border connection points.

Japan released an updated Hydrogen Basic Strategy in 2023, calling for 3mtpa clean hydrogen by 2030, 12mtpa by 2040, a 10% market share in electrolysers, 1,000 HRS sites, 800,000 FCEVs, and 30% hydrogen and 20% ammonia co-firing in demonstrator power plants. These targets, which are highly ambitious, are being matched by attempts to secure large supplies of liquid hydrogen from overseas.

Hydrogen policies and support mechanisms

	USA	EU	UK	RoW
Legislation	• Inflation Reduction Act (2022) • In limbo post-election	• REpowerEU (2022) • RED III (2009+) • Fit for 55 (2023)	• Hydrogen Strategy (2021) • UK Low Carbon Hydrogen Standard • Slow progress post-election	At least 75 countries and territories have clean hydrogen strategies
Scope	Green and blue	Overwhelmingly green. Blue lobby continues	Green and blue	Green dominates
Enablers	• 'Hydrogen Hubs' $8bn • IRA tax credits	• IPCEI (>E5bn so far) • Country level grants • EU Hydrogen Bank	• Net Zero Hydrogen Fund • UKIB / Great British Energy	Typically top down GW targets for 2030-50
Credits / subsidy	• Up to $3/kg H2 • Must emit <0.45tCO2/tH2 (green) • Must sequester 4t CO2 per t H2	EU Hydrogen Bank • Auction (2025) for E1.2bn Country-level CO2 credits, eg Germany E30/t CO2	Hydrogen Business Model CFD for revenue or capex • £2bn 1st tranche (HAR1) • Must be <20gCO2e/MJ H2 and 99.9% pure	>$100bn announced support
Targets	Est. 22GW/year electrolysis 2028 (1GW 2022)	Est. 300GW 2030 (<1GW 2022)	10GW 2030	$680 bn capex required for announced projects to 2030

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Hydrogen and e-fuels

Clean hydrogen can be combined with other elements to make replacements for fossil fuels and conventional ammonia. By combining clean hydrogen with air capture of CO_2, e-fuels can be carbon neutral. This 'e-fuel' sector is garnering much interest from developers as a way to bring clean hydrogen to established customers and markets, taking advantage of the GHG penalties on fossil fuel alternatives, and EU regulations under RED III for RFNBOs. There are several process choices for the use of hydrogen into e-fuels, including:

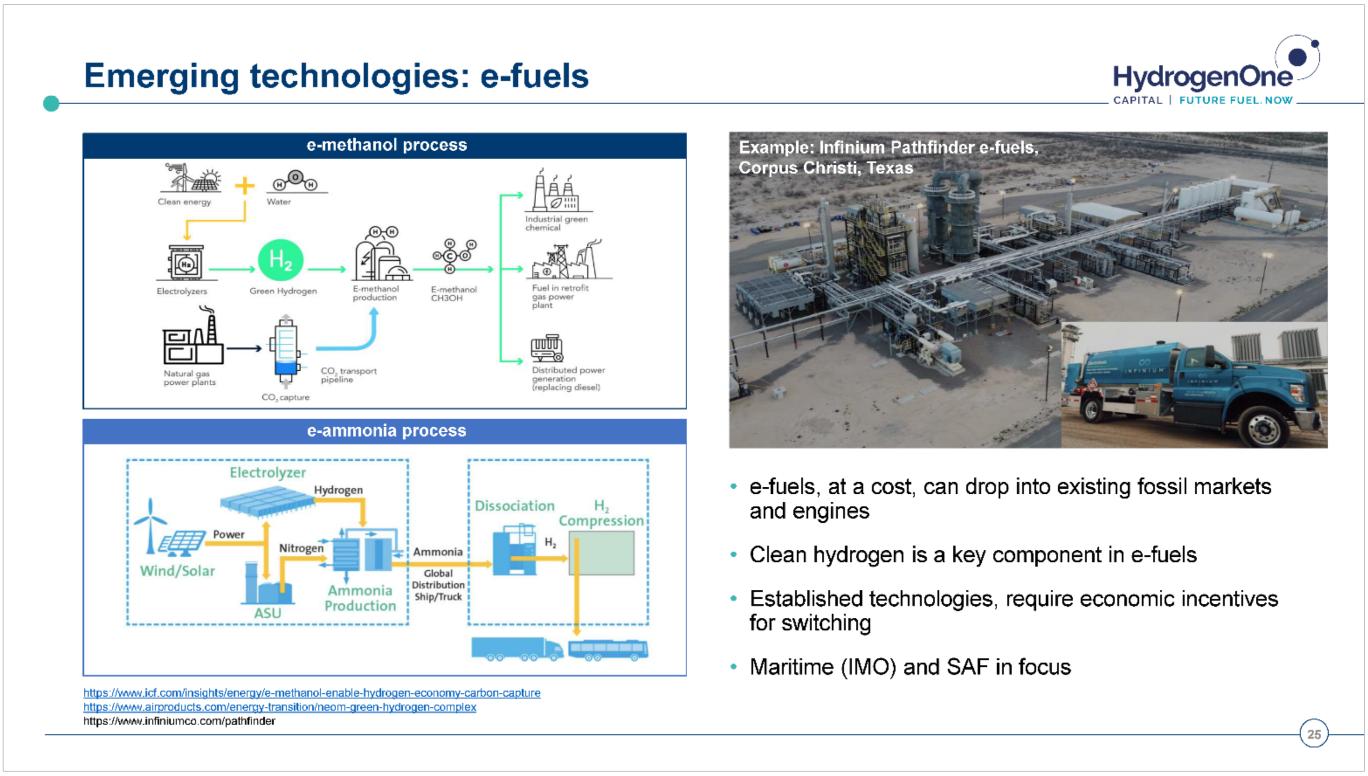
- Hydrotreated Esters and Fatty Acids (HEFA), refines vegetable oils, waste oils, or fats into SAF through a process that uses hydrogen (hydrogenation), to make e-fuels
- Fischer-Tropsch catalysis to make e-gasoline, e-diesel, synthetic aviation fuels through the combination with waste or direct air capture CO_2
- Methanol synthesis to create e-methanol, again through combination with waste or direct air capture CO_2
- Haber-Bosch process to combine with atmospheric nitrogen, to make green ammonia

These e-fuels can be used as e-gasoline, e-diesel, e-heating oil, e-kerosene, e-methanol, e-ammonia and e-gas and can completely replace conventional fuels. Moreover, due to their drop-in capability, e-fuels can be blended with conventional fuels in any ratio. Existing logistics, distribution and refuelling infrastructures, such as tank farms, tank lorries, pipelines and filling stations, can continue to be used.

Electrofuels leader Infinium is now successfully operating the world's first commercial scale facility making drop-in ready e-fuels in Corpus Christi, Texas. The project, known as Project Pathfinder, is a continuously operating plant producing synthetic, ultra-low carbon e-fuels that are being today's heavy transportation applications, such as Amazon trucks and in chemical processes.

Green ammonia can be used as an industrial gas in chemicals processes such as fertilizer manufacture, as a fuel, or an energy carrier for clean hydrogen. The NEOM project, currently under construction, aims to produce 1.2mtpa of green ammonia, based on green hydrogen, representing the world's largest green hydrogen and green ammonia plant to date.

Overall, there are a number of e-fuels plants in operation and under construction, and this theme is set for strong growth with the arrival of new IMO regulations to clean up shipping fuels, and RFNBO and SAF regulations and penalties in the EU.



FAQ

Blue versus Green

Blue hydrogen uses a natural gas feedstock, hence supports continued fossil fuels drilling and production. Advocates of green hydrogen, particularly companies involved in making renewable power and electrolysers, lobby against blue, and characterize it as a fossil fuel company front.

Reality: Blue hydrogen is a viable option for clean hydrogen today

- An ultra-low GHG emissions fuel
- Cost-competitive with grey hydrogen, whereas green hydrogen is more expensive
- Enables the continued use of natural gas wells and pipeline infrastructure that would otherwise have to be scrapped. This accounts for multi-trillions of dollars of sunk capital

Reality: Green hydrogen is a good short to medium-term option

- Complementary with blue and will scale up as renewable power grows
- Relatively high cost today, and a little behind blue in terms of cost curve

Reality: this is really about GHG emissions, not one technology vs another

- Blue hydrogen is supported by governments of countries with natural gas reserves and CCS geology. For example the UK, Norway and USA. Countries without these and/or with abundant renewables support green hydrogen e.g. Spain, Finland, Namibia, Morrocco
- Governments such as USA and UK require maximum GHG emissions intensity, properly-defined renewable power sources and fugitive gas strategies as part of the definition of “clean hydrogen”, and are not hung on green/blue/biogas etc as the source of the H2

Hydrogen is a greenhouse gas

Building out a hydrogen system will result in leaks, as is the case in the natural gas industry. Hydrogen will therefore contribute to global warming.

Reality: this is over-played. Hydrogen is a GHG, but is substantially less so than fossil

- Hydrogen could impact the distribution of ozone and methane in the atmosphere. However it oxidises quickly to water, or is absorbed by soils
- The climate impact would be about 0.6% of the fossil fuel economy, if hydrogen was to totally replace fossil
- Fugitive methane is 30X more harmful to the climate than CO_2. This overwhelmingly comes from old oil & gas wells. There a million of these in production in the USA alone, and over three million abandoned wells there. These are very hard to seal. The hydrogen industry will need to engineer to limit fugitive hydrogen, but this is on the ground, not under it, and is eminently doable

Green hydrogen uses too much water

Electrolysers use a lot of water, and will take away drinking water and farm water, etc

Reality: This is basically oil lobby push-back

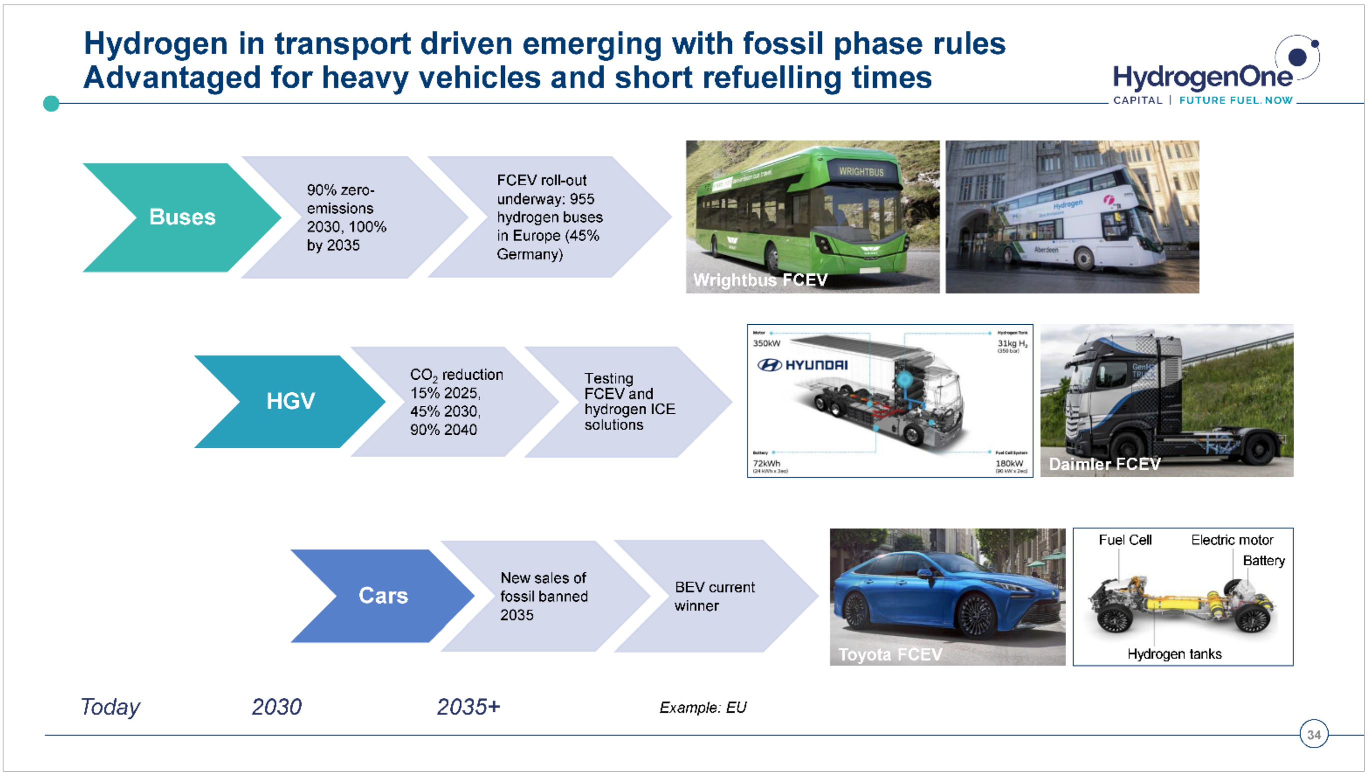
- Electrolysers split water into hydrogen and oxygen. The hydrogen is consumed by fuel cells that make electricity, and, er, water. The produced water doesn't go back to the original source, but it's not being destroyed
- You need 9-10kg of water to make 1kg of hydrogen in an electrolyser. Scale that up. If green hydrogen abates 10 billion tonnes/year of GHG, which is the assumption in the IPCC worst case climate change model (RCP 8.5), that would need 2.3 billion tonnes per year of hydrogen, made from 20.5 billion m3, per year of freshwater. That water accounts for only 1.5 ppm of Earth's available freshwater (0.0000015%)
- Irrigated agriculture uses 2,800 billion m3/year of water. You can do your part there, by eating fewer avocado pears. Fossil fuels extraction and power generation uses 250 billion m3/year of water. Which all needs to be turned off. This compares to 21 billion m3 / year for the future hydrogen economy
- A 20MW electrolyser module operated at average 50% capacity will consume approx. 17,000 tons of water per year. You may not want to put it in some place where farmers draw water from wells. The permits for that will get emotional. However, you could install desalination for your hydrogen water, which adds about $0.01/kg to hydrogen production cost. Electrolysers use demineralised water, which animals and plants don't drink anyway

Battery electric cars versus hydrogen fuel cells

Proponents of battery electric cars argue that hydrogen fuel cells don't compete.

Reality: battery and fuel cell vehicles both have great niches

- Battery electric is the best option for cars over short to medium distances
- Hydrogen fuel cells or hydrogen engines are a viable option for buses, trucks, trains (on tracks that are not electrified), fork lift and SUV. Battery technology is also improving for HGV, hence there will be competition between these solutions, with outcomes set by cost, access to hydrogen and access to charging networks. There is room for both in the market
- Hydrogen busses are emerging as a winning technology today, with roll-outs in many cities, especially in the EU



I don’t see hydrogen service stations

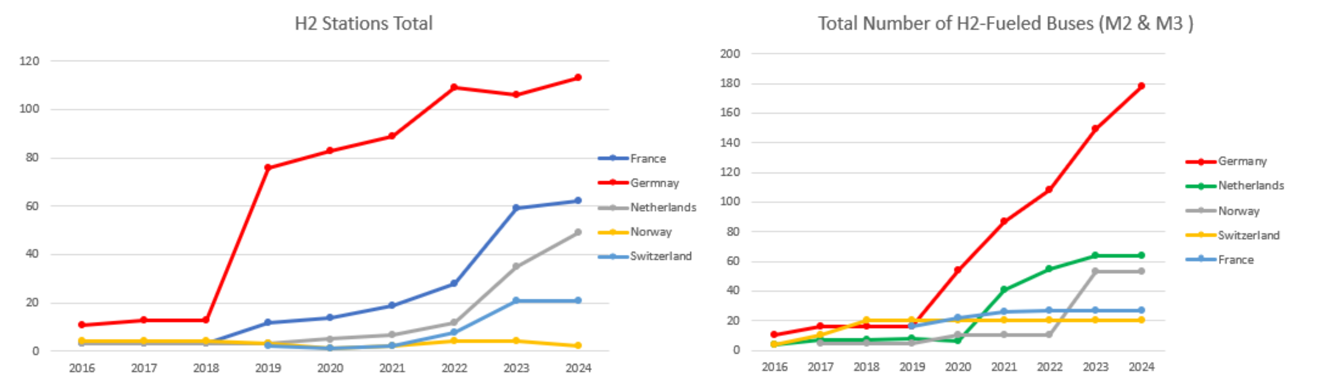
A common narrative in countries that aren’t leaders in hydrogen eg the UK.

Reality: strong growth in hydrogen services stations (aka “HRS”) in South Korea, Japan, Germany and California. Who’s buying? Trucks.

- Currently there are 1168 hydrogen refuelling stations were in operation worldwide. Europe had 248 hydrogen stations in 2024, 90 of which are in Germany. France is still second in Europe with 60 operating stations, followed by the Netherlands with 11, and Switzerland with 18 stations
- Germany is definitely one to watch… Westfalen, H2Mobility, Jet H2 Energy all have big plans to add significant capacity… and higher volume stations. H2Mobility alone are planning to grow from 90 stations to 300 by 2030
- Many of these sites are being developed in collaboration with HGV and car OEMs, and fossil fuel network owners, as they pilot hydrogen vehicles
- In the EU, the Alternative Fuels Infrastructure Regulation (AFIR) will require the deployment of a hydrogen refuelling station every 200 km along the Trans-European Transport Network (TEN-T) - more than 400 stations through 2030
- Many countries are planning for the phase out of fossil fuels from transport. This is a significant opportunity for hydrogen in heavy vehicles (trucks, buses). California, for example, has laws requiring all new passenger vehicles to zero emissions by 2035, and has targets and grants in place to increase hydrogen penetration

- Lots of headroom here… the USA alone has over 100,000 gasoline stations and globally there could be 400,000 of these climate change accelerators. The incumbents, mostly oil companies, are looking for ways to green up these otherwise-stranded assets

H2 stations and buses: Europe



Hydrogen refuelling sites growth

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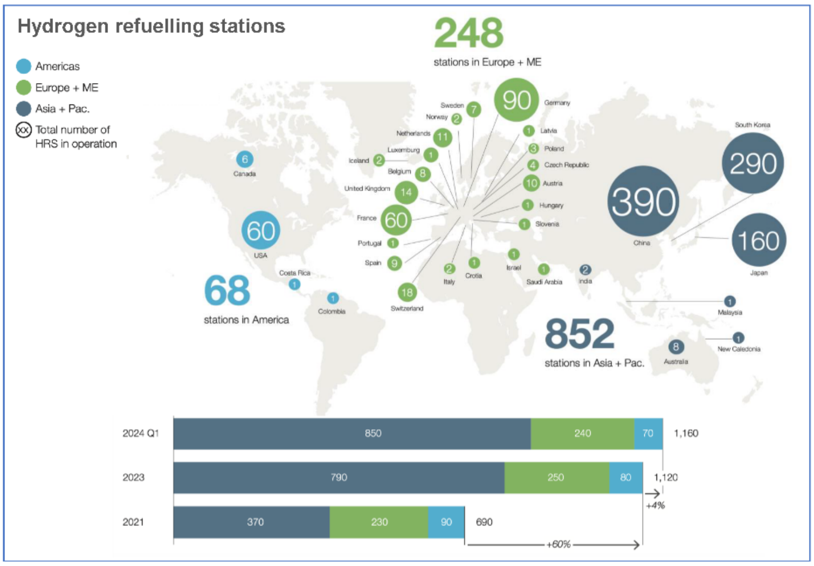

- Build-out of HRS. Often in collaboration with OEMs and oil products retailers
- South Korea and Japan plan to expand their networks to more than 600 stations each through 2030
- In the EU, the Alternative Fuels Infrastructure Regulation (AFIR) will require the deployment of a hydrogen refuelling station every 200 km along the Trans-European Transport Network (TEN-T) - more than 400 stations through 2030

https://hydrogencouncil.com/wp-content/uploads/2024/09/Hydrogen-Insights-2024.pdf

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Hydrogen fuel cells flight versus synthetic aviation fuel

This is a complex area, that is really in the innovation / R&D stage.

Reality: hydrogen fuel for flight has great potential but is not proven commercially

Hydrogen tanks that feed fuel cells to power turbo prop planes is a real option, and there are test flights underway today (e.g. ZeroAvia, Cranfield Aerospace). This could work for short haul commercial flight e.g. 50 seaters. Airbus is developing commercial jet engines to potentially burn hydrogen by storing fuel in the fuselage, but has pushed this timetable back to the mid 2030s due to the lack of hydrogen supply infrastructure.

Hydrogen has been used in jet engines in the Russian aviation sector. However, bulky and strong liquid hydrogen tanks are needed to fuel long distance flight, or innovation in hydrogen storage, due to hydrogen's low energy density compared to traditional jet fuel.

A viable alternative is to combine clean hydrogen with CO_2 to make synthetic aviation fuel (SAF). Over time, SAF may well be the best route to jet decarbonisation, but the costs are prohibitive currently.

Clean hydrogen is high cost and won't compete with fossil fuels

These arguments centre on the cost and time required to build up hydrogen infrastructure versus producing lower carbon, oil and gas via CCS.

Reality: these are old arguments that are rapidly falling away.

Economic recovery from COVID and Russia's invasion of Ukraine have resulted in more 'normal' fossil fuel prices c.$70-$120 Brent. This is a markedly different position than the 2015-2020 "$40" world and reflects the real replacement cost of fossil fuels.

These are headline hydrogen supply costs on a $/kg basis:

- Grey $1-8/kg: established market price. The large range is related to the natural gas cost. This source of hydrogen will be phased out under penalties for example EU RED III.
- Blue $3-11/kg: includes CCS cost
- Green $1-6/kg: in the range of grey and blue. The low-end is in the US, including IRA tax credits, should they materialise

Fossil fuels market share will fall over time in the energy transition. They are expected to become more expensive due to carbon penalties and / or mitigation costs. But there will be "low carbon fuels" with things like CCS applied.

Hydrogen supply projects can generate an attractive developer IRR at a sales price of E7/kg or higher, in projects sitting in the EU. Buyers are prepared to pay these prices in order to mitigate GHG penalties.

Can you drill for native hydrogen, like you do for oil & gas?

Hydrogen can be produced from geological reservoirs, and you don't need Green hydrogen at all. This is White hydrogen.

Reality: This is something certainly worth following, but there are quite some challenges

Native hydrogen has been found in volcanic rocks, salt mines and sedimentary rocks, most notably in water wells drilled in Mali in the 1980s, and put online by Petroma Inc, in 2012. Geologists are not too clear on how it got there – is this gas that comes from igneous (hot) rocks, does it come from hot water reactions with metamorphic rocks (serpentanites), or is it gas emitted by microbes (biogenic gas), and how it is trapped? Predicting the presence of this gas is very difficult – oil & gas exploration wells have a 1 in 10 chance of success, or worse, after 150 years of geologic studies to improve the odds, and the cost of onshore wells can be $15 million each.

Expect to see geologists working over records of old wells, and fund raising to re-drill them for hydrogen. The gas may or may not be near markets, and hence the transport cost could be prohibitive versus manufactured hydrogen. Fuel cells need extremely clean hydrogen. Native hydrogen will likely need clean up facilities, as does natural gas, which can cost $100s of millions. Native hydrogen could have a role but the fiscal and technical risks are high. A major discovery in or near and industrial market such as the EU or US would be a big moment for clean hydrogen, and could catalyse the sector.

You can't put hydrogen into natural gas networks, can you?

Various conspiracy theories that hydrogen will corrode pipes, it will leak, and that it can't be burnt in power plants and domestic boilers.

Reality: this is an out-of-date concept.

Town gas (from coal) in the UK was 20% hydrogen ie before North Sea gas. In the UK, HyDeploy has trialled a 20% hydrogen blend with natural gas into current domestic boilers (2021). Pure hydrogen boilers are on the market today, although they are pricey. Gas turbines that use hydrogen in power plants are being developed in the Netherlands, Japan and the USA. Natural gas grid blending is permitted at low levels (1-2%) in Germany, for example, today, and the thresholds are likely to increase over time.

Key terminology

Jargon	Explained	Key players examples
Electrolysers	Decades-old technology going through a renaissance to improve efficiency and lower supply cost. Car to shipping container-sized units. Electricity enters/leaves via an anode/cathode, and passes through an electrolyte to release heat, hydrogen and oxygen. There are various types of electrolysers, reflecting innovation and the specific purpose of the installation	
…Alkaline electrolysers ("AEL")	The original. The workhorse today. Uses potassium and sodium hydroxide electrolyte, and nickel plates. Slower response time to the 'ups and downs' of renewable power, but technology improvements are addressing this. MW Scale, and relatively low cost	Cummins, McPhy, NEL, Sunfire, HydrogenPro, Thyssenkrupp Nucera, John Cockerill
…Proton exchange membrane electrolysers ("PEM")	Newer tech – uses a proton exchange membrane. Faster response times and work off a low power load. Popular for green hydrogen systems. Below MW scale but upscaling fast. Contain things like platinum, iridium and PFAS ("forever chemicals"), hence require recycling and permit work-arounds	Cummins, ITM, NEL, Ohmium, Siemens Energy
…Solid oxide electrolysers ("SOEC")	Solid ceramic electrolyte. Uses heat by-product to warm up the electrolyte, meaning it will run with less electricity. A technology that runs hot (700 degrees) and is high efficiency	Elcogen, Haldor Topsoe, Sunfire
…Anion exchange membrane electrolysers ("AEM")	Newer tech, which uses a low concentration alkaline than AEL. Safer to handle, and can use lower purity water than AEL. Really at the innovation stage	Enapter, Sunfire
Fuel cells	Anode/cathode system that mixes air (O_2) with hydrogen to release electricity, heat and water. As in electrolysers, the system uses an electrolyte hence there are PEM, solid oxide and other types. Brick to cooker-sized units. Used in trucks, trains, planes, and large buildings as an electricity source	Ballard, Toshiba, Plug Power, Bramble Energy
CCUS	Carbon capture, use and storage. CO_2 "streams" are extracted from refineries, power plants etc., and piped to wells that have been drilled into geological reservoirs, where the CO_2 is injected and stored. Some systems use the CO_2 for other manufacturing processes	Large oil & gas companies e.g., Exxon, Shell, BP, Equinor, INEOS, industrial gas companies e.g. Linde, Air Liquide

Jargon	Explained	Key players examples
Grey hydrogen (aka 'brown' and 'black')	Today's 70mtpa industry. Hydrogen made by reforming coal, gas, oil, with consequent greenhouse gas ("GHG") emissions (2X UK annually). Steam methane reforming ("SMR") is the main process used as well as Autothermal Reforming ("ATR")	Air Liquide, Air Products, Linde
Blue Hydrogen	Takes grey hydrogen, but captures and stores the GHG in geological reservoirs ("CCS"). Matches the skill-sets of integrated oil companies. Sometimes called 'low carbon'	Shell, Valero, Equinor, Aramco, BP
Green hydrogen	Uses green electricity from wind or solar to power electrolysers, which split water into oxygen and hydrogen. A rapidly-emerging technology that is on the cusp of large scale roll out	Air Products, Iberdrola, Shell, Engie, ERM, multiple smaller players
Other colours of hydrogen	***Yellow*** – takes excess nuclear electricity into electrolysis. aka Pink ***Turquoise*** – splits natural gas into hydrogen and solid carbon ***White*** – naturally-occurring hydrogen trapped in geological reservoirs. No-one really knows how this works ***Gold*** – microbes eat up oil in depleted reservoirs and let off hydrogen, or in-situ burning of oil reservoirs, which apparently does this as well	HiiROC, Monolith Cemvita Mali
Power-to-X	Conversion of excess electricity supply to storable fuel eg hydrogen and ammonia	Everyone in electrolysis is interested in this
Liquid hydrogen	This is at -259.2 degrees C. This is a lot colder than liquefied natural gas (LNG), -162 degrees C and more expensive to handle. Better to make green ammonia with clean hydrogen, which boils at -33 degrees C. Hence the interest in green ammonia as a clean hydrogen carrier	Maersk Air Liquide Fortescue Future Fuels
Solid state storage & liquid carriers	Innovation around combining hydrogen with metal micro-mesh into "metal hydrides" or "solid hydrogen". Takes up more space than compressed gas, but works for stationary power. Liquid carriers combine hydrogen with organic compounds such as benzyl toluene, resulting in a liquid at ambient temperature and pressure – a liquid organic hydrogen carrier ("LOHC"). Needs a chemical process at each end of the chain – hydrogenation and dehydrogenation	GKN Hydrogen Hydrogenious