Hydrogen gas has long been recognised as an alternative to fossil fuels and a potentially valuable tool for tackling climate change.

Now, as nations come forward with net-zero strategies to align with their international climate targets, hydrogen has once again risen up the agenda from Australia and the UK through to Germany and Japan.

In the most optimistic outlooks, hydrogen could soon power trucks, planes and ships. It could heat homes, balance electricity grids and help heavy industry to make everything from steel to cement.

But doing all these things with hydrogen would require staggering quantities of the fuel, which is only as clean as the methods used to produce it. Moreover, for every potentially transformative application of hydrogen, there are unique challenges that must be overcome.

In this in-depth Q&A – which includes a range of infographics, maps and interactive charts, as well as the views of dozens of experts – Carbon Brief examines the big questions around the "hydrogen economy" and looks at the extent to which it could help the world avoid dangerous climate change.

What is hydrogen and how could it help tackle climate change?

Hydrogen is the lightest and most abundant element in the universe. It is also an explosive and clean-burning gas that contains more energy per unit of weight than fossil fuels.

In a hydrogen economy, hydrogen would be used in place of the fossil fuels that currently provide four-fifths (https://www.carbonbrief.org/solar-is-now-cheapest-electricity-in-history-confirms-iea) of the world's energy supply (https://www.bloomberg.com/news/articles/2020-11-17/primary-energy-vs-final-energy-why-replacing-fossil-fuels-won-t-be-so-hard?sref=Oz9Q3OZU) and emit the bulk (https://ourworldindata.org/ghg-emissions-by-sector) of global greenhouse gas emissions.

This could aid climate goals because hydrogen only emits water when burned and can be made without releasing CO2. (Its production currently emits 830m tonnes of CO2 (https://webstore.iea.org/download/direct/2803) [MtCO2] each year.)

The hydrogen economy could be all-encompassing. Or it could fill a series of niches, depending on hydrogen availability, cost and performance relative to alternatives, for each potential application.

In between these two extremes, there is still the potential for hydrogen to play a hugely significant role in reaching net-zero emissions, requiring a dramatic scaling up of its production and use.

“Are you for or against hydrogen? That seems to be the wrong question. I think the question is: where do you really need to use it?” says Dr Jan Rosenow (https://www.raponline.org/staff/jan-rosenow/) of the Regulatory Assistance Project (https://www.raponline.org/).

Hydrogen could help tackle “critical” hard-to-abate sectors, such as steel and long-distance transport, says Timur Gül (https://www.iea.org/authors/timur-gul), head of the Paris-based International Energy Agency (https://www.iea.org/) (IEA) energy technology division and lead on its major 2019 report (https://www.iea.org/reports/the-future-of-hydrogen) on the future of hydrogen. He tells Carbon Brief:

> “I think hydrogen has its place, has quite an important place…but I think if you’re aiming towards net-zero emissions, you don’t look for building a hydrogen economy, you look for a decarbonised energy sector. It’s a means to an end.”

Hydrogen can be made by splitting water with electricity – electrolysis – or by splitting fossil fuels or biomass with heat or steam, using “reforming (https://www.energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming)” or “pyrolysis (https://link.springer.com/referenceworkentry/10.1007%2F978-1-4939-2493-6_956-1#:~:text=Pyrolysis%20is%20a%20well%2Dknown,in%20the%20absence%20of%20oxygen.)”. Any CO2 can be captured and stored.

Hydrogen can be stored, liquified and transported via pipelines, trucks or ships. And it can be used to make fertiliser, fuel vehicles, heat homes, generate electricity or drive heavy industry.

This potential hydrogen “economy” is shown in the graphic, below. The illustrations, with numbered captions from one to three, show how hydrogen could be made, moved and used.

Graphic by Tom Prater.

Some advocates for a hydrogen economy describe an expansive vision of the future where it replaces most of the societal, economic and geopolitical positions now occupied by fossil fuels.

Dr Saehoon Kim, head of the fuel cell division at Hyundai, told an Energy UK webinar (https://twitter.com/EnergyUKcomms/status/1281508334722584578) in July:

> “In the past, our technology and industry was all about collecting oil, delivering oil and using oil. And now, in the future, it will be collecting sunshine, delivering sunshine and using sunshine – and what will make that possible is hydrogen.”

This vision would see the sun's energy – in the form of solar radiation and wind – turned into hydrogen, using electrolysis, and then transported around the world.

As a globally traded commodity, hydrogen could then remake the map of geopolitics, ending reliance on fossil fuel exporting nations and improving energy security for importers.

In its 2019 report, the IEA adds industrial development and skilled jobs to the list of potential advantages for hydrogen. It says hydrogen is flexible and versatile, able to act as a fuel, as well as an energy carrier between locations and – via storage – between different times of day or year.

It could also extend the life of fossil fuels and associated infrastructure, such as gas pipelines, the IEA's 2019 hydrogen report (https://www.iea.org/reports/the-future-of-hydrogen) says:

> "[I]f CCUS [carbon capture, use and storage] is used to reduce the CO2 intensity of fossil fuel hydrogen production, that would enable some fossil fuel resources to continue to be used."

City gas pipes maintenance under ground. Credit: Andor Bujdoso / Alamy Stock Photo.

Moreover, the hydrogen economy could help to balance the use of variable renewables to generate electricity. Electrolysis could absorb excess supplies and, when there is little wind or sun, hydrogen could be burned in gas turbines (https://twitter.com/JesseJenkins/status/1286295109265432576?s=09) to ensure electricity demand is met. The IEA explains:

> "By producing hydrogen, renewable electricity can be used in applications that are better served by chemical fuels. Low-carbon energy can be supplied over very long distances, and electricity can be stored to meet weekly or monthly imbalances in supply and demand."

This means hydrogen could help reinforce and connect the largely separate energy systems that are used today for heat, power, industry and transportation, an idea known as "sector coupling (https://www.cleanenergywire.org/factsheets/sector-coupling-shaping-integrated-renewable-power-system)".

And the technology needed to make and use hydrogen has the potential to benefit from the policy and cost reduction experience that has seen renewables become cheap (https://www.carbonbrief.org/solar-is-now-cheapest-electricity-in-history-confirms-iea).

Given all these advantages, the IEA's report says "it may be tempting to envisage an all-encompassing low-carbon hydrogen economy in the future". But it adds:

> "However, other clean energy technology opportunities have greatly improved recently, most importantly solutions that directly use electricity, which means that the future for hydrogen may be much more one of integration into diverse and complementary energy networks. This is especially so since the use of hydrogen in certain end-use sectors faces technical and economic challenges compared with other (low-carbon) competitors."

In a similar vein, Micheal Liebreich, senior contributor to BloombergNEF, wrote in a recent article (https://about.bnef.com/blog/liebreich-separating-hype-from-hydrogen-part-one-the-supply-side/): "On the surface, [hydrogen] seems like the answer to every energy question." But he adds: "Sadly, hydrogen displays an equally impressive list of disadvantages."

Advantages of hydrogen

> - Burns cleanly, releasing only water and energy.
> - Stores more energy per unit of weight than most other fuels.
> - Can be made from low-carbon sources.
> - Can be used as a fuel, to transport energy from one place to another, as a form of energy storage or as a chemical feedstock.
> - Can be used to decarbonise "hard to abate" sectors with few alternatives.
> - Offers wider benefits for energy security, industrial strategy and air quality.

Disadvantages of hydrogen

> - Almost all production today is from high-carbon sources.
> - Currently expensive to produce and cost reductions are uncertain.
> - Bulky and expensive to transport and store.
> - Inefficient to produce, raising costs and requiring a larger energy supply overall, with even faster scaling up of clean energy production.
> - Supply and value chains for its use are complex and need coordination.
> - Needs new safety standards and societal acceptance.

The IEA says challenges include high costs, which make hydrogen uncompetitive today, with uncertainty over how costs will develop over time (see below). It adds:

> "Hydrogen comes with safety risks (https://www.hse.gov.uk/horizons/current-issues/energy-topics/hydrogen.htm), high upfront infrastructure costs and some of the industrial dynamics of fossil fuel supply and distribution, especially when paired with CCUS [carbon capture, use and storage (https://www.iea.org/fuels-and-technologies/carbon-capture-utilisation-and-storage)]. It is not yet clear how citizens will react to these aspects of hydrogen."

The IEA also says there is a risk of a chicken-and-egg situation because of the complexity of hydrogen supply and value chains (https://www.cisl.cam.ac.uk/education/graduate-study/pgcerts/value-chain-defs), which makes gradual deployment more difficult.

For example, replacing fossil gas for building heat would rely on the availability of large quantities of low-carbon hydrogen and suitably upgraded infrastructure to distribute and safely burn the fuel.

There is also uncertainty over government and policy support for hydrogen, though a growing list of countries are developing dedicated hydrogen strategies (see below).

Low efficiency is another significant challenge, with more energy being wasted at each step in the production and use of hydrogen than for many alternatives.

The IEA says: "Hydrogen-based fuels could take advantage of existing infrastructure with limited changes in the value chain, but at the expense of efficiency losses."

The Economist (https://www.economist.com/science-and-technology/2020/07/04/after-many-false-starts-hydrogen-power-might-now-bear-fruit) says hydrogen is "inescapably inefficient", while the Energy Technology Institute's (https://www.eti.co.uk/) chief engineer wrote in 2018 (https://www.eti.co.uk/news/is-hydrogen-the-missing-piece-in-the-energy-jigsaw-to-meet-2050-targets): "A strategy to enforce comprehensive adoption of hydrogen across the economy looks grossly inefficient based on current understanding of the relevant technologies."

The figure below shows why electric vehicles are several times more efficient than hydrogen fuel cell vehicles, or those running on synthetic fuels derived from hydrogen.

Transport & Environment
@transenv

Electric vs hydrogen cars?
Battery electric cars are at least three times more efficient than hydrogen fuel cell cars due to energy losses.

7:47 AM · Aug 22, 2017

It is a similar story (https://www.theccc.org.uk/wp-content/uploads/2018/11/Hydrogen-in-a-low-carbon-economy.pdf) when comparing (https://www.agora-energiewende.de/en/publications/the-future-cost-of-electricity-based-synthetic-fuels-1/) electric heat pumps with hydrogen boilers, or when looking at the efficiency of storing excess electricity (https://twitter.com/Sustainable2050/status/1309779720293277696?s=20) in the form of hydrogen for later use.

The IEA explains:

> "All energy carriers (https://www.energy.gov/eere/articles/hydrogen-clean-flexible-energy-carrier), including fossil fuels, encounter efficiency losses each time they are produced, converted or used. In the case of hydrogen, these losses can accumulate across different steps in the value chain. After converting electricity to hydrogen, shipping it and storing it, then converting it back to electricity in a fuel cell, the delivered energy can be below 30% of what was in the initial electricity input.

> "This makes hydrogen more 'expensive' than electricity or the natural gas used to produce it. It also makes a case for minimising the number of conversions between energy carriers in any value chain. That said, in the absence of constraints to energy supply, and as long as CO2 emissions are valued, efficiency can be largely a matter of economics, to be considered at the level of the whole value chain."

Indeed, conventional energy systems based on fossil fuels are already highly inefficient (https://www.ft.com/content/217b0f2d-eaf9-434e-92c6-f5afb89ff084), with combustion engine cars returning as little as 20% of the energy in petrol as useful forward motion. Similarly, the average efficiency (https://www.ge.com/power/transform/article.transform.articles.2018.mar.come-hele-or-high-water) of coal-fired power plants is just 33%.

This suggests low efficiency is not a fundamental barrier to the use of hydrogen. Instead, low efficiency may hold back hydrogen via higher costs and the need for a larger energy supply.

Finally, although cost, efficiency and technical performance are all important factors for hydrogen to address, "there are some really critical drivers beyond techno-economics", says Thomas Blank (https://rmi.org/people/thomas-koch-blank/), senior principal for industry and heavy transport at the Rocky Mountain Institute (https://rmi.org/).

Referring to the EU's recently published hydrogen strategy (see below), he tells Carbon Brief:

> "Ultimately for the EU, it's not necessarily driven by cost, it's driven by security of energy supply, reduction of exposure to Vladimir Putin [for Russian oil and gas imports], job creation. Those aspects of the hydrogen opportunity are underplayed at the moment and they are what is going to drive things forward."

Which countries are exploring the use of hydrogen?

Last year, the International Energy Agency (https://www.iea.org/) (IEA) produced a major report on the future of hydrogen (https://www.iea.org/reports/the-future-of-hydrogen), noting it was "currently enjoying unprecedented political and business momentum".

It described 2019 as a "critical year" for the energy carrier and outlined a steady increase in policies and research supporting its use in energy applications.

Influential organisations, including the IEA, Hydrogen Council (https://hydrogencouncil.com/en/) and BP (http://bp.com/), have all revealed their visions for its future significance and others have (https://www.h2-view.com/story/2020-marks-the-start-of-the-decade-of-hydrogen/) heralded (https://www.telegraph.co.uk/business/2020/08/26/2020s-will-decade-hydrogen/) the 2020s as the "decade of hydrogen".

The pipeline for "green" hydrogen – produced using renewable electricity – is expanding rapidly, nearly tripling (https://www.greentechmedia.com/articles/read/mega-projects-help-double-green-hydrogen-pipeline-in-just-five-months) in just five months earlier this year. However, these projects still make a marginal contribution to the global energy system.

Only six of the 197 parties (https://www.climatewatchdata.org/ndc-search?query=hydrogen&searchBy=query&section=none) to the 2015 Paris Agreement (https://www.carbonbrief.org/interactive-the-paris-agreement-on-climate-change) mentioned "hydrogen" in their first nationally determined contributions (https://www.carbonbrief.org/explainer-what-are-intended-nationally-determined-contributions) to the deal, but interest is growing as a wave of countries, encouraged by net-zero targets (https://twitter.com/CarbonBrief/status/1325828048277688320), set out national hydrogen strategies.

A recent review (https://www.weltenergierat.de/wp-content/uploads/2020/10/WEC_H2_Strategies_finalreport.pdf) by the World Energy Council's (https://www.worldenergy.org/impact-communities/members/entry/germany) German chapter found that 20 countries have introduced such strategies or are "on the verge of doing so".

The map below is based on updated analysis by the council shared with Carbon Brief. It shows another 33 countries moving in this direction. This led the group to conclude that by 2025 these strategies will likely cover countries representing over 80% of global GDP.

Extent of hydrogen support in a selection of countries, including national strategies, pilot and demonstration projects and policy discussions. Based on a figure from a report by Ludwig-Bölkow-Systemtechik GmbH (LBST) and the World Energy Council's German chapter. Map by Joe Goodman for Carbon Brief.

One of the most significant announcements was the European Commission's "hydrogen strategy (https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf) for a climate-neutral Europe", released in July 2020, which includes an ambitious target of 40 gigawatts (GW) of European electrolyser capacity to produce "green" hydrogen by 2030.

For context, between 2000 and 2019, a total capacity of just 0.25GW of green hydrogen projects was deployed globally, according to (https://www.woodmac.com/news/editorial/the-future-for-green-hydrogen/) consultancy Wood Mackenzie.

In a press conference (https://twitter.com/EU_Commission/status/1280804957436948480) launching the strategy, European Commission vice-president Frans Timmermans described "clean" hydrogen as "crucial" for the EU's "green deal (https://ec.europa.eu/clima/policies/strategies/2050_en)", which targets net-zero emissions by 2050.

> "Much of the energy transition will focus on direct electrification, but in sectors like steel, cement, chemicals, air traffic, heavy-duty transport, shipping, we need something else."

This ambition has been bolstered by several European nations, including Germany (https://www.bundesfinanzministerium.de/Content/DE/Standardartikel/Themen/Schlaglichter/Konjunkturpaket/2020-06-03-konjunkturpaket-beschlossen.html), Portugal (https://storage.googleapis.com/cclow-staging/ann865wmn0snjfl75hrtnbkjt7ry?GoogleAccessId=laws-and-pathways-staging%40soy-truth-247515.iam.gserviceaccount.com&Expires=1603209727&Signature=H%2BoEVh6i6utZ4rCAj0jazG2hqJsbh1OPlrUspIMBP% content-disposition=inline%3B+filename%3D%22Estrategia+Nacional+para+o+Hidrogenio+DRAFT+publicacao.pdf%22%3B+filenar 8%27%27Estrat%25C3%25A9gia%2520Nacional%2520para%2520o%2520Hidrog%25C3%25A9nio%2520DRAFT%2520publ content-type=application%2Fpdf) and the Netherlands (https://www.government.nl/documents/publications/2020/04/06/government-strategy-on-hydrogen), releasing hydrogen strategies of their own, some in the context of a "green recovery (https://www.carbonbrief.org/coronavirus-tracking-how-the-worlds-green-recovery-plans-aim-to-cut-emissions)" from the Covid-19 pandemic.

Under pressure to keep up with European neighbours, UK ministers have said (https://www.bloomberg.com/news/articles/2020-09-10/u-k-government-eyes-world-leading-hydrogen-market?sref=Oz9Q3OZU) they will soon announce a "world-leading" hydrogen strategy to help reach its 2050 net-zero goal (https://www.carbonbrief.org/in-depth-qa-the-uk-becomes-first-major-economy-to-set-net-zero-climate-goal). The National Grid has said hydrogen will be "required" (https://www.carbonbrief.org/in-depth-hydrogen-required-to-meet-uk-net-zero-goal-says-national-grid) to meet this target.

Acknowledging the "flurry" of recent national hydrogen strategies in a recent Environmental Audit Committee (https://committees.parliament.uk/committee/62/environmental-audit-committee) hearing (https://parliamentlive.tv/event/index/460af480-3e7e-47da-a668-cf10eaaf158d), UK business secretary Alok Sharma said the government expected to release its own "early on next year [2021]".

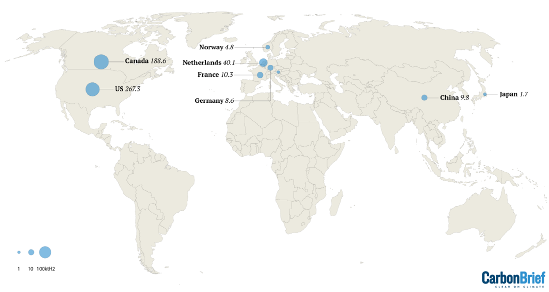
Prime minister Boris Johnson's "10-point plan (https://www.carbonbrief.org/media-reaction-boris-johnsons-10-point-net-zero-plan-for-climate-change)" for a "green industrial revolution" mentioned (https://www.gov.uk/government/news/pm-outlines-his-ten-point-plan-for-a-green-industrial-revolution-for-250000-jobs) spending of "up to £500m ($667m)" on hydrogen, including a target of 5GW low-carbon hydrogen production capacity over the next decade.

This is significantly less (https://www.businessgreen.com/blog-post/4023618/point-plan-green-industrial-revolution-great-missing) than some other European nations. Germany alone has said it will spend €9bn on clean hydrogen production and exporting the technology overseas, but with the same target of 5GW domestic capacity by 2030.

The map below illustrates current and planned hydrogen capacity around the world and shows how Europe is currently leading with its plans for future production.

(Toggle between the two using the switch in the top-left corner.)

Currently operational



Current and planned low-carbon hydrogen production capacity, thousands of tonnes. Note that the capacity of production from fossil fuels with CCS is rated as the amount that would be zero-carbon, based on the proportion of CO2 emissions that are captured and stored. Planned projects may not all go ahead as they are at various stages of development, including schemes without clear timelines or firm investment decisions. Source: Updated version of the publicly available IEA hydrogen projects database (https://www.iea.org/reports/hydrogen-projects-database), as provided to Carbon Brief by the IEA. Map by Tom Prater for Carbon Brief.

However, in his speech, Timmermans said that while Europe has been leading, other nations are catching up, referring to plans (https://www.greentechmedia.com/articles/read/us-firm-unveils-worlds-largest-green-hydrogen-project#:~:text=The%20%245%20billion%20plant%20will,fueled%20buses%2C%20Air%20Products%20said.) for a large hydrogen plant in Saudi Arabia powered by 4GW of wind and solar. "[Hydrogen] has become the rockstar of new energies all across the world," he said.

The competition over this market and rush to fund new projects was dubbed "the hydrogen wars" by one energy professional recently speaking to Bloomberg (https://www.bloomberg.com/news/articles/2020-11-01/-hydrogen-wars-pit-europe-v-china-for-700-billion-business?sref=Oz9Q3OZU).

Japan, in particular, has been exploring hydrogen as an energy source since the 1970s and in its 2017 hydrogen strategy (https://www.meti.go.jp/english/press/2017/pdf/1226_003b.pdf) announced plans to build the first "hydrogen-based society".

Prior to the event's postponement due to Covid-19, the Japanese government intended to showcase its advances (https://www.energy-reporters.com/storage/tokyo-olympics-to-showcase-hydrogen-progress/) at the 2020 Tokyo Olympics, using hydrogen to power the Olympic flame and a fleet of 100 buses serving the games. South Korea has been (https://fuelcellsworks.com/news/south-korea-to-create-three-hydrogen-cities-by-2022/) another early adopter.

Other nations, including Australia (https://www.industry.gov.au/data-and-publications/australias-national-hydrogen-strategy) and New Zealand (https://www.mbie.govt.nz/dmsdocument/6798-a-vision-for-hydrogen-in-new-zealand-green-paper#:~:text=Green%20hydrogen%20is%20a%20platform%20that%20will%20help%20reduce%20global%20emissions.&t have released plans to mobilise their abundant renewable resources and become major exporters of green hydrogen to parts of Asia (https://uk.reuters.com/article/us-japan-energy-hydrogen/japan-aims-to-set-up-commercial-hydrogen-fuel-supply-chain-by-2030-idUKKBN2700PM) and Europe.

European Commissioner for European Green Deal Frans Timmermans speaks during a news conference at the European Commission headquarters. Credit: Reuters / Alamy Stock Photo.

However, China is seen as Europe’s biggest rival when it comes to green hydrogen technology and competition between the two powers could help (https://www.cleanenergywire.org/news/europe-vies-china-clean-hydrogen-superpower-status) bring down prices.

Already the world’s largest (https://www.weltenergierat.de/wp-content/uploads/2020/10/WEC_H2_Strategies_finalreport.pdf) producer and user of hydrogen, China has been developing hydrogen fuel cells for around 20 years. Former science minister Wan Gong, who pioneered the nation’s electric car strategy, has said (https://www.bloomberg.com/news/articles/2019-06-12/china-s-father-of-electric-cars-thinks-hydrogen-is-the-future?sref=Oz9Q3OZU) it “should look into establishing a hydrogen society”.

Energy companies, such as Shell (https://www.shell.com/energy-and-innovation/new-energies/hydrogen/_jcr_content/par/keybenefits_150847174/link.stream/1496312627865/6a3564d61b9aff43e087972db5212 h2-study-new.pdf) and BP (https://www.bp.com/en/global/corporate/news-and-insights/press-releases/bernard-looney-announces-new-ambition-for-bp.html), are also coming forward with hydrogen plans, committing to deploying low-carbon hydrogen projects as components of their net-zero emissions goals.

Meanwhile, the US, once considered a leader in hydrogen technology, has been (https://www.greentechmedia.com/articles/read/how-the-u.s-can-catch-up-on-a-green-hydrogen-economy) falling behind in recent years.

(While the map above shows considerable planned hydrogen capacity, it is skewed by one large project (https://www.powermag.com/group-says-it-will-launch-worlds-largest-green-hydrogen-project/) proposed by the energy company SGH2, which says it intends to have a facility producing hydrogen from biomass in operation by 2023.)

A recent report (https://static1.squarespace.com/static/53ab1feee4b0bef0179a1563/t/5e7ca9d6c8fb3629d399fe0c/1585228263363/Road+M backed by several of the country's oil firms and car manufacturers stated that hydrogen has a "key role to play in maintaining US global energy leadership":

> "Other countries, such as Germany, Japan and China, are developing hydrogen infrastructure and investing in the groundwork for a hydrogen economy. The US should not fall behind."

How much hydrogen is needed to limit climate change?

In more than two dozen interviews for this article, there was broad consensus that hydrogen will be needed to avoid dangerous climate change by reaching net-zero emissions. There is less agreement on how much hydrogen the world will need and which sectors it will be used in.

Like electricity, hydrogen is an "energy carrier (https://www.energy.gov/eere/articles/hydrogen-clean-flexible-energy-carrier)" or "energy vector". In simple terms, this means it is a convenient way to store, move and use energy extracted from other sources.

Crucially, the production of both electricity and hydrogen can be decarbonised. (See: Which countries are exploring the use of hydrogen? (http://Which-countries)) These zero-carbon energy carriers will be vital for reaching net-zero.

While electrification plays the leading role (https://www.ipcc.ch/site/assets/uploads/sites/2/2019/02/SR15_Chapter2_Low_Res.pdf) in pathways identified (https://www.carbonbrief.org/in-depth-qa-ipccs-special-report-on-climate-change-at-one-point-five-c) by the Intergovernmental Panel on Climate Change (https://www.ipcc.ch/) (IPCC), it cannot currently unlock some sectors, such as long-distance transport.

This makes hydrogen "essential" to reaching net-zero, says Dr David Joffe (https://twitter.com/david_joffe?lang=en), head of carbon budgets at the UK's advisory Climate Change Committee (https://www.theccc.org.uk/). He tells Carbon Brief:

> "In our view, you should be looking to electrify wherever you can. Where that's prohibitively expensive, or where it's not feasible, that's the role that you're looking for hydrogen."

Unlike electricity, the energy stored in hydrogen is carried in relatively stable chemical bonds rather than a more ephemeral electrical charge. This means its energy is easier to store, transport and convert into other molecules for use as fuels or chemical feedstocks.

"There are always going to be some applications where electrification is not appropriate," says Meredith Annex (https://twitter.com/meredith_annex?lang=en), acting lead on hydrogen and head of heating and cooling at BloombergNEF (https://about.bnef.com/):

> "That might be because you need a molecule of fuel for the [higher] energy density (https://afdc.energy.gov/fuels/hydrogen_basics.html#:~:text=The%20energy%20in%202.2%20pounds,driving%20range%20of% or for the chemical reaction, or for the durability in terms of storage. So we see hydrogen and low-carbon fuels as a general catch-all as being indispensable for a net-zero economy."

Even though hydrogen is expected to play a lesser role than electricity in reaching net-zero emissions, its production and use could still need to scale up dramatically from today.

Chris Stark
@ChiefExecCCC

I see we're back to debating hydrogen vs electrification again.

Here's a secret from @theCCCuk big fancy #NetZero computer model: we need *lots* of both.

#ANDnotOR

GIF

3:39 AM · Sep 24, 2020

537 210 people are Tweeting about this

Just how dramatically hydrogen expands will depend on policy decisions, societal choices, relative costs and technical performance, across each potential application of the fuel.

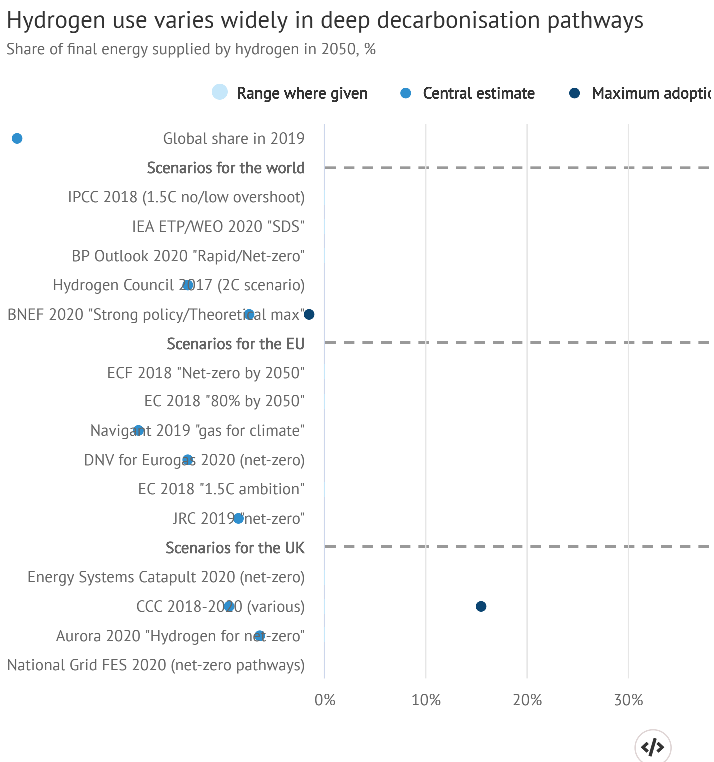
There is also uncertainty over how much low-carbon hydrogen will cost to make in the future and how easy it will be to successfully deploy the fuel at scale, across multiple sectors of the economy.

As a result, there is a broad range of hydrogen use in pathways that model how the world – and individual countries or regions – can cut their emissions to avoid dangerous climate change.

Carbon Brief analysed hydrogen use in a range of deep decarbonisation scenarios to gauge the level of adoption overall and in specific end-use sectors.

The chart below shows the share of final energy (https://www.bloomberg.com/news/articles/2020-11-17/primary-energy-vs-final-energy-why-replacing-fossil-fuels-won-t-be-so-hard?sref=Oz9Q3OZU) supplied by hydrogen, in 2050, in deep decarbonisation pathways for the world (top), the EU (centre) and the UK (bottom).

Each row shows the findings of a single report or organisation, with a range of hydrogen shares indicated for different scenarios, as appropriate, by the light blue bars. Central estimates and maximum potentials are shown as mid-blue and dark blue circles, respectively.



Share of final energy supplied by hydrogen, %. Global share in 2019 (top) versus shares in 2050 for the world (upper), EU (central) and the UK (lower). Ranges (light blue bars) indicate the spread of relevant scenarios. Central estimates (mid blue dots) and maximum adoption (dark blue) also shown. Source: Carbon Brief analysis of listed studies and analysis (https://ec.europa.eu/jrc/en/science-update/hydrogen-use-eu-decarbonisation-scenarios) by the European Commission's Joint Research Centre (https://ec.europa.eu/info/departments/joint-research-centre_en). See linked sheet (https://docs.google.com/spreadsheets/d/e/2PACX-1vTDZmXUpsJOBNMcjp2769UVcRyPZbxEdHOIsi839cYA5M0q_T8G0ZUF8P_2wqO8_vd46hFR5EDr2Hns/pubhtml) for references. Chart by Joe Goodman for Carbon Brief using Highcharts (https://www.highcharts.com/)

For the global studies in the top segment of the chart, hydrogen meets anything between zero and 30% of final energy in 2050. The top end is a theoretical maximum rather than a realistic potential.

The scenarios that cover the EU have a similar range, with a maximum of 23% in a net-zero by 2050 pathway from the European Commission's Joint Research Centre (https://ec.europa.eu/info/departments/joint-research-centre_en).

Notably, the UK pathways analysed for this article include up to half of final energy in 2050 being met by hydrogen, much higher than the share in EU and global studies.

Carbon Brief understands new advice from the Climate Change Committee (https://www.theccc.org.uk/) (CCC), due on 9 December, will have scenarios with hydrogen's share at less than one fifth to one third of the total.

Importantly, a scenario's hydrogen use depends on several factors, including the assumptions of the modellers (https://www.carbonbrief.org/qa-how-integrated-assessment-models-are-used-to-study-climate-change), the level of detail in their models and the ambition of the modelled pathways.

Former UK government adviser Guy Newey (https://es.catapult.org.uk/staff/guy-newey/) has argued (https://twitter.com/guynewey/status/1237447147378933760) that "in many ways hydrogen [is] the big winner" after the UK raised its ambition from an 80% emissions cut by 2050 to 100%. This is supported by research (https://linkinghub.elsevier.com/retrieve/pii/S1364032117314089) showing a correlation between a scenario's ambition and hydrogen uptake.

Low rates of hydrogen use in any particular model or scenario might reflect outdated assumptions about its cost or technical potential, relative to other decarbonisation options for each end use.

Similarly, scenarios showing widespread use of hydrogen might reflect over-optimistic assumptions about the potential cost reductions that can be achieved in hydrogen production and use, or might see its output scaling up at unrealistically rapid rates.

"[H]ydrogen has historically had a limited role in influential global energy scenarios," according to a study (https://pubs.rsc.org/en/content/articlehtml/2020/se/c9se00833k) from Dr Sheila Samsatli (https://researchportal.bath.ac.uk/en/persons/sheila-samsatli) at the University of Bath, with international colleagues. It adds:

> "The results and conclusions obtained from an oversimplified model can be misleading and possibly erroneous. In the context of hydrogen, if a technology does not appear in the results then it is not possible to determine whether this is because of an inherent disadvantage of the technology or whether it is due to the inadequacy of the model to represent the technology's benefits."

Looking at the global studies in the chart, above, the lowest levels of hydrogen use are in the IPCC's 2018 special report on 1.5C (https://www.carbonbrief.org/in-depth-qa-ipccs-special-report-on-climate-change-at-one-point-five-c). This low uptake is likely to partly reflect the age of the modelling literature available at the time, with hydrogen likely to have been considered costly.

Hydrogen features more strongly in BP's latest energy outlook (https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/energy-outlook/bp-energy-outlook-2020.pdf), building on "more comprehensive modelling of the role that hydrogen and bioenergy may play in the energy transition".

Its "net-zero" pathway – which BP says is broadly in line with 1.5C scenarios – sees hydrogen use reaching 58 exajoules (EJ) by 2050 and meeting around 15% of final global energy demand.

BP notes that the use of hydrogen in this pathway is at the "top end of the range" of IPCC scenarios, where demand is between 15-60EJ at the point when emissions reach net-zero.

The company's outlook adds that this "may reflect that many of the IPCC scenarios were compiled before the increase in policy and private-sector interest in hydrogen over the past few years".

In a report (https://data.bloomberglp.com/professional/sites/24/BNEF-Hydrogen-Economy-Outlook-Key-Messages-30-Mar-2020.pdf) published in March 2020, BloombergNEF (https://about.bnef.com/) set out an even stronger case for hydrogen. It identified maximum technical potential for the gas to meet 30% of final global energy demand in 2050.

In a pathway that limits warming to 1.5C above pre-industrial levels and energy use overall is much lower, BNEF sees hydrogen meeting 24% of final global energy demand, as shown in the chart above.

The company's more recent "new energy outlook (https://about.bnef.com/new-energy-outlook/)" sees 800m tonnes of hydrogen (MtH2) being used in 2050 to meet a quarter of final global energy demand, while keeping warming to well-below 2C.

If this were all made using electrolysis, it would require 36,000 terawatt hours (TWh) of electricity. "[T]his is 38% more electricity than is produced in the world today," BNEF notes.

BNEF's new energy outlook expects hydrogen use to be split between the power sector (30%), industry (30%), transport (25%) and buildings (15%), as shown in the chart below.

Nat Bullard
@NatBullard

Replying to @NatBullard

24/ @BloombergNEF #BNEFNEO 2020: Global hydrogen demand under our cleanelectricity and green-hydrogen pathway reaches 801Mt in 2050. Around 30% of this goes to power generation and another 30% goes to industry. about.bnef.com/new-energy-out...

8:24 AM · Oct 27, 2020

14 See Nat Bullard's other Tweets

Another recent study is the International Energy Agency (IEA) Energy Technology Perspectives (https://www.iea.org/reports/energy-technology-perspectives-2020), published in September 2020. This sees hydrogen use meeting less than 7% of final energy demand in 2050, of which transport (44%), industry (28%), power (19%) and buildings (9%).

By 2070, in a scenario keeping warming well-below 2C, the IEA sees hydrogen meeting 13% of final energy demand, with this total spread unevenly between sectors. Hydrogen would meet large shares of energy use in shipping and aviation, but hardly any for buildings, as shown below right.

Left: Hydrogen use in the IEA Energy Technology Perspectives sustainable development scenario, millions of tonnes of oil equivalent per year (left axis) and as a share of final energy (right axis), 2019-2070. Right: Hydrogen share of final energy in 2070, for each end use sector. Source: IEA Energy Technology Perspectives 2020 (https://www.iea.org/reports/energy-technology-perspectives-2020).

The study by Samsatli and colleagues concludes that industry and heavy-duty transport offer the greatest opportunities for hydrogen use. It adds that if large-scale hydrogen infrastructure is built to serve these sectors, then the gas could also offer flexibility elsewhere, such as the power sector.

Emma Pinchbeck (https://twitter.com/elpinchbeck?lang=en), chief executive of trade group Energy UK (https://www.energy-uk.org.uk/), tells Carbon Brief: “The strongest business case for hydrogen is in sectors where there are few alternatives.”

This might include shipping, heavy industry or heating, Pinchbeck says, though she notes: “Electrification is going to have to be a big part of the answer on heat.” Pinchbeck adds:

> “Fundamentally, a lot of the future value in the energy market will be in electrons and flexibility. So hydrogen needs to work out how it’s going to fit into that model…Hydrogen is a really attractive solution, but the challenge is about how it can be commercially attractive to fit into the gaps in the economy, where electricity can’t do it.”

Why is hydrogen being ‘hyped’ again now?

Hydrogen has been lauded by many newspaper editorials and world leaders (https://www.thetimes.co.uk/article/the-times-view-on-boris-johnsons-enthusiasm-for-hydrogen-fuels-gold-jg5b7v0n2) as a fix to today’s problems, from driving (https://www.theguardian.com/environment/2020/jul/19/can-a-hydrogen-boom-fuel-a-green-recovery-for-britain?) a “green recovery” following the Covid-19 pandemic to reducing (https://www.telegraph.co.uk/news/2020/07/18/britain-can-lead-world-transmuting-water-fuel/?) the UK’s reliance on China for electric vehicle batteries.

This enthusiasm for hydrogen as an energy solution is not new. The first hydrogen-powered (https://books.google.co.uk/books/about/Hydrogen_Internal_Combustion_Engine_Vehi.html?id=WpdVYAAACAAJ&redir_esc=y) internal combustion engine was constructed in 1807 and debate around the use of hydrogen from electrolysers to replace coal emerged (https://twitter.com/nworbmot/status/1317449761218285568` early as 1863.

Dr Tom Brown (https://nworbmot.org/), an energy-system modeller at the Karlsruhe Institute of Technology (https://www.kit.edu/english/index.php), outlined some of this early history in a series (https://twitter.com/nworbmot/status/1317449761218285568) of recent Twitter threads. He tells Carbon Brief:

> "The fact is that…anything basically can be done with hydrogen if you're smart enough. People basically realised that very early on and it keeps recurring as a theme, but it doesn't really become relevant until you have very low-cost power."

An early example of this came from hydrogen electrolysers of more than 100 megawatts (MW) built from the 1920s to supply the fertiliser industry, using cheap hydropower in places such as Norway and India.

Tom Brown
@nworbmot

Despite the current hype, there's nothing new about electrolytic hydrogen.

- 100 MW electrolysers since late 1920s for fertiliser and heavy water

- 100 GWh salt cavern storage since 1960s

- 4500 km hydrogen pipelines today

What was missing was abundant low cost power.

9:31 AM · Jul 31, 2020

292 134 people are Tweeting about this

These early efforts were edged out as electricity demand grew in other sectors and cheap fossil fuels became available for hydrogen production. Nevertheless, there have since been several "hype cycles (https://www.ft.com/content/ccbdd868-5499-11ea-90ad-25e377c0ee1f)" and government drives to get hydrogen off the ground.

The term "hydrogen economy" was first coined (https://royalsocietypublishing.org/doi/pdf/10.1098/rsta.2016.0400) in 1970 by the chemist Prof John Bockris (https://en.wikipedia.org/wiki/John_Bockris), who had a vision (https://pubs.acs.org/doi/abs/10.1021/cen-v055n040.p027) of a world powered by solar- and nuclear-generated hydrogen.

In the same year, a paper (https://www.researchgate.net/publication/30822365_Toward_a_liquid_hydrogen_fuel_economy) titled "towards a liquid hydrogen fuel economy" by Prof Lawrence Jones (https://lsa.umich.edu/physics/people/emeritus/lwjones.ht a physicist at the University of Michigan, concluded:

> "As a pollution-free fuel, [hydrogen] must be seriously considered as the logical replacement for hydrocarbons in the 21st century."

The development of hydrogen fuel cells (https://www.power-technology.com/comment/standing-at-the-precipice-of-the-hydrogen-economy/) for commercial applications began shortly after as the Organization of Petroleum Exporting Countries (https://www.opec.org/opec_web/en/) (OPEC) imposed an oil embargo (https://history.state.gov/milestones/1969-1976/oil-embargo) on the US, Japan and western Europe (https://www.britannica.com/topic/oil-crisis), driving up prices and prompting a search for alternative fuels.

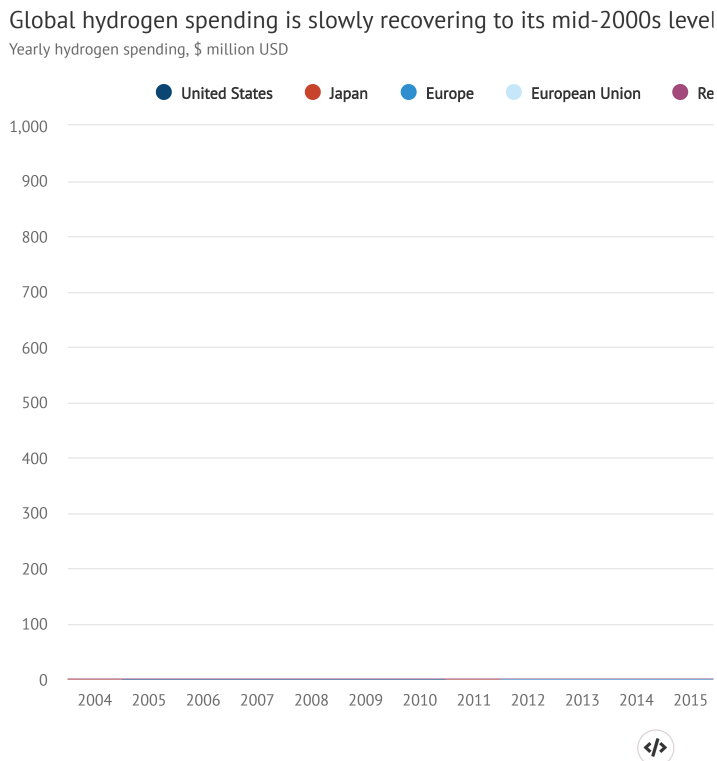
Interest waned as the embargo lifted, new fossil fuels were exploited and oil prices fell. The next "false dawn (https://www.oxfordenergy.org/publications/hydrogen-and-decarbonisation-of-gas-false-dawn-or-silver-bullet/)" of the hydrogen economy came in the 1990s (https://www.wired.com/1997/10/hydrogen-3/), when carmakers in particular poured investment into the technology.

This time, according to (https://www.iea.org/reports/the-future-of-hydrogen) the IEA, oil prices "remained low through the second half of the decade, stifling support that could have moved these projects closer to the mainstream".

U.S. President George W. Bush delivers the 2003 State of the Union address. Credit: Reuters / Alamy Stock Photo.

Amid concerns about "peak oil (https://www.bbc.co.uk/news/science-environment-18353962)" in 2003, US president George W Bush announced a $1.2bn hydrogen fuel initiative (https://www.energy.gov/sites/prod/files/2014/03/f12/hpwgw_doe_paster.pdf) in his state of the union address (https://www.carbonbrief.org/state-of-the-union-how-climate-and-energy-have-featured-since-1989) in the hope that "the first car driven by a child born today could be powered by hydrogen".

However, once again this hype was relatively short-lived and, as the chart below shows, after a peak in 2008 global government spending on hydrogen went into decline. (Note that the chart only includes the 30 IEA member countries and the EU. This does not include China.)



R&D spending on hydrogen and fuel-cell technology in 30 countries that are members of the International Energy Agency and the European Union. Source: IEA (https://www.iea.org/subscribe-to-data-services/energy-technology-rdd). Chart by Joe Goodman for Carbon Brief using Highcharts (https://www.highcharts.com/).

"When the hydrogen economy didn't really materialise in the second half of the 2000s it got put on the back burner again," Gniewomir Flis (https://twitter.com/gnievchenko), an energy and climate adviser at the thinktank Agora Energiewende (https://www.agora-energiewende.de/), tells Carbon Brief.

Climate change has been a consistent theme in hydrogen discussions, but concerns about oil supply and price have dominated and road vehicles have been seen as the main target market.

Therefore, in each round of interest, whenever oil costs have dipped or new fossil fuel supplies have been unlocked, the excitement around hydrogen has tended to subside.

Prof Ad van Wijk (http://profadvanwijk.com/), a professor of future energy systems at the Delft University of Technology (https://www.tudelft.nl/en/), tells Carbon Brief that this time the circumstances are different:

> “What you see now is, of course, a very different system change and that is that renewables have become very cheap. That is the major driver.”

Falling costs (https://www.iea.org/commentaries/hydrogen-the-missing-link-in-the-energy-transition) of renewables have brought a fresh wave of enthusiasm as the abundant, low-cost power many see (https://twitter.com/nworbmot/status/1289206955534213121) as a prerequisite for hydrogen’s success now appears achievable.

Crucially, the climate targets of the Paris Agreement (https://www.carbonbrief.org/interactive-the-paris-agreement-on-climate-change) in 2015 are unlikely to be met unless decarbonisation reaches every corner of the economy, including “hard-to-decarbonise (https://www.powerengineeringint.com/emissions-environment/hydrogen-the-hope-for-hard-to-decarbonise-sectors/)” sectors, such as steel production, shipping and aviation.

The International Renewable Energy Agency (https://www.irena.org/) (IRENA) suggests (https://www.irena.org/publications/2018/Sep/Hydrogen-from-renewable-power) hydrogen could be the “missing link” in the global energy system, helping to cut emissions in all of these sectors that are difficult to electrify.

Sunita Satyapal (https://www.energy.gov/eere/contributors/sunita-satyapal), director of the US Department of Energy’s (https://www.energy.gov/) hydrogen office, tells Carbon Brief that the availability of relatively cheap hydrogen means interest now extends far beyond road transport:

“A key benefit of hydrogen is that it can provide value for various applications and help integrate sectors,” she says.

Meanwhile, Flis points out that oil and gas majors have started (https://www.bloomberg.com/news/articles/2020-06-25/big-oil-s-long-bet-on-hydrogen-offers-a-climate-lifeline?sref=Oz9Q3OZU) pushing hydrogen as an alternative fuel. “They started to realise that they will have to eventually change to something,” he says.

CEOs from some of the world’s biggest oil producers, as well as car manufacturers and industrial firms, formed the Hydrogen Council (https://hydrogencouncil.com/en/) in 2017 to promote hydrogen, and interest from bodies including the IEA and IRENA has helped push it into the spotlight.

The recent launch (https://www.businessgreen.com/news/4023823/green-energy-giants-team-launch-renewable-hydrogen-coalition) of the Renewable Hydrogen Coalition (https://windeurope.org/newsroom/press-releases/renewable-hydrogen-coalition-will-position-europe-as-world-leader-on-renewable-hydrogen/) by key trade bodies shows how the wind and solar industries are also backing hydrogen, with key trade bodies pledging to help “develop the business models and markets that will make renewable hydrogen mainstream”.
Ben Gallagher (https://www.woodmac.com/about-us/our-people/ben-gallagher/), an analyst specialising in the hydrogen economy at consultancy Wood Mackenzie, tells Carbon Brief that, ultimately, the most important factor is that this technology simply “makes more economic sense…than ever before”.

How is low-carbon hydrogen produced?

Demand for hydrogen has already been rising steadily for decades and stands at (https://www.iea.org/reports/the-future-of-hydrogen) around 70Mt, according to the IEA. The vast majority of this is made from fossil fuels, with high CO2 emissions.

The agency says that satisfying all of this demand using electricity would require 3,600 terawatt hours (TWh) of dedicated production – "more than the total annual electricity generation of the EU".

An additional 45Mt of hydrogen is used in industries, such as steel and methanol production, in a mixture with other gases.

Virtually all pure hydrogen today is used in applications such as oil refining and fertiliser production, not to heat buildings, drive trucks or generate electricity.

In a report (https://www.woodmac.com/our-expertise/focus/transition/2020-hydrogen-landscape/#:~:text=Key%20findings%20from%20the%20report,70%25%20of%20global%20hydrogen%20demand.) on the status of the industry, released in early 2020, Wood Mackenzie (https://www.woodmac.com/) concluded that while hydrogen demand has grown 28% over the past decade this growth is "small compared to many other new technologies". (Wind and solar output has rocketed (https://www.carbonbrief.org/solar-is-now-cheapest-electricity-in-history-confirms-iea) over the same period.)

"If demand for low-carbon hydrogen grows, the market will see an upsurge in growth. But we have not seen that explosion yet," Wood Mackenzie notes, in an unfortunately worded press release.

The term "low-carbon hydrogen" is essential here because while all hydrogen burns without producing greenhouse gas emissions, the climate impacts of different production methods varies considerably.

Hydrogen pipe. Credit: Thyssenkrupp Steel Europe / Alamy.

Hydrogen production is often known by different colours. For the purposes of decarbonisation, the two most prominent varieties are "green" and "blue". (The IEA avoids (https://www.iea.org/reports/the-future-of-hydrogen) these labels as the environmental impact of production can vary widely within a single colour category.)

Types of hydrogen production

- Green: Generated using electrolysis powered by renewable electricity.
- Blue: Production is based on fossil fuels but with CO_2 emissions captured.
- Grey: Made using fossil gas with no emissions captured.
- Black: Made using coal.
- Brown: Made using lignite.
- Turquoise: Heat is used to split fossil gas in a process known as "pyrolysis".
- Purple, pink or yellow: Electricity and heat from nuclear reactors could both be used to produce hydrogen, but there is no widely agreed colour for such methods.
- Not agreed: Production from biomass.

Green hydrogen (https://www.greentechmedia.com/articles/read/green-hydrogen-explained]) is produced by electrolysis, a process that uses an electrical current to split water into hydrogen and oxygen, using power generated from renewables. This label is sometimes misleadingly applied to hydrogen derived from grid electricity, which will only be as "renewable" as the grid itself is.

Blue hydrogen, on the other hand, is generally produced by reacting methane gas with steam and then capturing and storing the resulting CO_2 emissions. In steam methane reforming (https://www.energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming#:~:text=In%20steam%2Dmethane%20reforming%2C%20methane,for%20the%20reaction%20to%20proceed.), the most common method, fossil gas is both burned to fuel the process and used as the feedstock.

As it stands, the vast majority of hydrogen is not green or blue, but instead is made using fossil fuels without any carbon capture. Production methods based on coal, lignite and gas without carbon capture and storage (CCS) are termed "black", "brown" and "grey", respectively.

According to (https://www.iea.org/reports/the-future-of-hydrogen) the IEA, 76% of hydrogen comes from gas and 23% from coal – the latter mostly in China – with just 2% coming from electrolysis. Less than 0.7% of current hydrogen production is from low-carbon green or blue supplies.

Andreas Graf
@andreasgraf

Replying to @andreasgraf

To sum up, publically available and harmonized data on current hydrogen production seems to be difficult to come by. This makes it difficult to know which energy sources our current production is sourced from and seems like a problematic position to develop policy from.

7:26 AM · Sep 11, 2020

7 See Andreas Graf's other Tweets

Moreover, hydrogen production consumes 6% of all the world's gas and 2% of all coal and generates 830MtCO2 each year, slightly more than the annual emissions of Germany.

In the near term, grey hydrogen is likely to remain the cheapest and most widespread production route as no low-carbon production method is currently cost-competitive against it. (See: "How much is it going to cost?")

For the purposes of achieving net-zero emissions, hydrogen production will need to be switched from grey to green and blue. The role these two varieties play is discussed in the next section – "Does 'blue' hydrogen have a place in a net-zero future?"

Beyond the basic palette of colours, there are a handful of other production methods – some of them low-carbon – that could contribute to future hydrogen demand.

Hydrogen can also be generated using nuclear power to drive electrolysis. According to the IEA there is "no established colour" for hydrogen produced via nuclear power, but reports have variously referred to it as "yellow (https://www.world-nuclear.org/information-library/energy-and-the-environment/hydrogen-production-and-uses.aspx)", "pink (https://www.h2-view.com/story/hydrogen-clearing-up-the-colours/)" and "purple (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7326412/#b0060)".

In addition, heat from nuclear reactors could have applications in hydrogen production by producing steam for more efficient (https://inldigitallibrary.inl.gov/sites/sti/sti/4480292.pdf#:~:text=Efficient%20water%2Dsplitting%20for%20hydrogen,proc electrolysis or fossil gas-based steam methane reforming.

In the longer term, the very high temperatures of advanced nuclear reactors could directly extract hydrogen from water by thermochemical splitting (https://www.energy.gov/eere/fuelcells/hydrogen-production-thermochemical-water-splitting#:~:text=Thermochemical%20water%20splitting%20uses%20high,or%20no%20greenhouse%20gas%20emissions.) Such projects are still in the very early stages of development.

Prof Robin Grimes (https://www.imperial.ac.uk/people/r.grimes), nuclear chief scientific adviser at the UK's Ministry of Defence, recently authored a Royal Society paper (https://royalsociety.org/-/media/policy/projects/nuclear-cogeneration/2020-10-7-nuclear-cogeneration-policy-briefing.pdf) on "nuclear cogeneration", the process of using heat from reactors in "hard-to-decarbonise" sectors, as well as producing electricity.

While no large-scale hydrogen production facility using nuclear energy has so far been built anywhere, Grimes tells Carbon Brief the two industries would benefit from greater integration:

> "Rather than nuclear being orphaned as something that can only produce baseload electricity, actually nuclear is part of the solution because…its heat can be used directly when the electricity is not needed. That's this cogeneration idea."

Using nuclear power to produce hydrogen was a popular idea in the early days of hydrogen research and is still being (https://www.euractiv.com/section/energy/news/franco-german-team-up-aims-to-drive-hydrogen-production-forward/) advocated by France, Russia (https://asia.nikkei.com/Editor-s-Picks/Interview/Russia-plans-to-export-hydrogen-to-Asia-in-green-shift) and the US (https://www.energy.gov/ne/articles/could-hydrogen-help-save-nuclear#:~:text=Nuclear%20power%20plants%20can%20produce,and%20electricity%20it%20reliably%20provides.&text= nations that already rely on nuclear for much of their power supply.

Civaux Nuclear Power Plant, Vienne, Poitou-Charentes region, France. Credit: imageBROKER / Alamy Stock Photo

A report (https://www.lucidcatalyst.com/hydrogen-report) by consultancy Lucid Catalyst (https://www.lucidcatalyst.com/) argues that the amount of hydrogen required to reach international climate targets is "far more than can be produced with renewables", making nuclear-sourced hydrogen a necessity.

The Lucid report contends that there is a clear path to cheap nuclear energy and that this, combined with cheap high-temperature electrolysers, will make nuclear-driven production the cheapest way to make hydrogen, in part due to higher conversion efficiency.

However, the solid oxide electrolysis cells (SOECs) required to make electrolytic hydrogen using nuclear heat are far more expensive than other varieties, according to the IEA. It puts (https://www.iea.org/reports/the-future-of-hydrogen) their cost at up to $5,600 per kilowatt today, around three to five times higher than other electrolysers.

The agency also notes (https://www.iea.org/reports/the-future-of-hydrogen) in its hydrogen report that SOECs are the "least developed electrolysis technology" and are yet to be commercialised.

Hydrogen can also be produced using biomass, although the IEA concludes (https://www.iea.org/reports/the-future-of-hydrogen) the need for complex processing and lack of sufficient cheap and sustainable biomass (https://www.carbonbrief.org/ccc-uk-should-move-away-from-large-scale-biomass-burning) makes this less appealing than other "low-carbon" techniques. No colour has been assigned (https://twitter.com/gnievchenko/status/1304107048666308611?s=03) to hydrogen from biomass.

There is also "turquoise (https://www.h2-international.com/2020/05/15/turquoise-hydrogen-a-game-changer/)" hydrogen, generated as a by-product of methane pyrolysis (https://www.advancedsciencenews.com/decarbonizing-natural-gas-methane-fuel-without-carbon-dioxide/), which uses heat to split fossil gas into hydrogen and carbon.

This is still a niche strategy (https://www.tno.nl/en/focus-areas/energy-transition/roadmaps/towards-co2-neutral-fuels-and-feedstock/hydrogen-for-a-sustainable-energy-supply/ten-things-you-need-to-know-about-hydrogen/) that only exists on a small scale, but there has been (https://www.nature.com/articles/s41558-020-0891-0) industry interest given the potentially useful applications of its carbon by-product.

Turquoise hydrogen has potential as a low-emission option if the process is powered by renewables or nuclear and the resulting carbon is stored.

However, a recent study (https://www.sciencedirect.com/science/article/pii/S2590174520300155) concluded that like blue hydrogen it would still generate substantial emissions due to the production of the gas used to provide the necessary heat for the process.

Does 'blue' hydrogen have a place in a net-zero future?

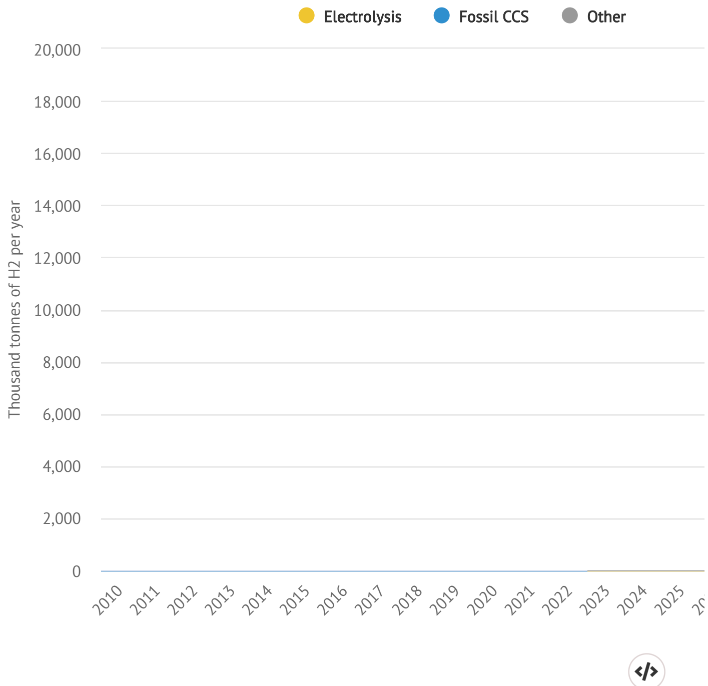
There is considerable debate around blue hydrogen's contribution to achieving net-zero emissions. Some see a significant role for it, while others say that at most it should be used as an interim solution while green hydrogen is scaled up.

Meanwhile, some campaigners (https://eeb.org/europes-hydrogen-strategy-a-gift-to-fossil-fuel-companies-ngo-response/) and scientists (https://www.thetimes.co.uk/article/fossil-fuel-companies-misleading-prime-minister-on-green-hydrogen-j7v6wnn6q) have argued that blue hydrogen locks nations into a future of fossil fuel use and methane emissions leakages, meaning it should be avoided altogether.

There are currently plans to rapidly scale up both green and blue capacity around the world, as the chart below indicates. (Note that not all proposals will be realised and around half the planned capacity in the chart comes from just three major schemes: Solena's "plasma gasification" proposal (https://www.sgh2energy.com/projects/#proheader) in the US, marked "other" in the chart; the H21 blue hydrogen scheme (https://www.h21.green/) in the UK; and the Asian Renewable Energy Hub (https://asianrehub.com/) planned in Australia.)

There are plans to rapidly scale clean hydrogen production...

...but not all planned projects will go ahead



Estimated global hydrogen production capacity, in thousands of tonnes per year, divided into green hydrogen produced using renewable electrolysis (yellow), blue hydrogen made using fossil gas with carbon capture and storage (blue) and hydrogen produced using other techniques (grey). The column on the far right indicates projects for which no completion date has been assigned. Not all project proposals will go ahead. Source: Updated version of the publicly available IEA hydrogen projects database (https://www.iea.org/reports/hydrogen-projects-database), as provided to Carbon Brief by the IEA. Chart by Joe Goodman for Carbon Brief using Highcharts (https://www.highcharts.com/).

The pipeline of projects in the chart, above, roughly mirrors the split in production methods envisaged in the net-zero scenario of BP's energy outlook (https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/energy-outlook/bp-energy-outlook-2020.pdf), which has 16% of final energy consumption coming from hydrogen in 2050 – half green and half blue.

Oil majors are not alone in picturing a future for blue hydrogen. The Climate Change Committee (CCC) indicative pathway (https://www.theccc.org.uk/wp-content/uploads/2019/05/Net-Zero-Technical-report-CCC.pdf) to net-zero for the UK relies primarily on blue hydrogen, although Carbon Brief understands updated guidance, expected in December, will point to a larger share for green.

Proponents of blue hydrogen (https://www.spglobal.com/platts/en/market-insights/latest-news/electric-power/101920-blue-and-green-hydrogen-essential-for-energy-transition-but-key-challenges-remain-bank) argue that it is necessary for net-zero as it is both more immediately available and allows for better use of renewable electricity resources in the short term. It could also (https://www.cedelft.eu/en/publications/download/2585) be integrated into existing fossil gas infrastructure.

At the energy outlook's launch, BP group chief economist Spencer Dale said (https://www.petroleum-economist.com/articles/low-carbon-energy/energy-transition/2020/rush-to-green-hydrogen-may-be-counterproductive-bp) focusing exclusively on green hydrogen would "constrain the pace at which the hydrogen economy can grow".

A report by energy trade expert Ralf Dickel (https://www.oxfordenergy.org/authors/ralf-dickel/) for the Oxford Institute for Energy Studies (http://www.oxfordenergy.org) concluded that overreliance on green hydrogen would mean "cannibalising the success of renewable electricity in the power sector…And for what? Blue hydrogen can do the job of decarbonising the non-electric sector starting now".

Governments have shown support for blue hydrogen, at least in the short term. Julian Critclow (https://www.gov.uk/government/people/julian-critchlow), director general of energy transformation and clean growth in the UK's Department for Business, Energy and Industrial Strategy (https://www.gov.uk/government/organisations/department-for-business-energy-and-industrial-strategy) (BEIS) has said (https://parliamentlive.tv/event/index/460af480-3e7e-47da-a668-cf10eaaf158d)it has "a role in the middle times".

In an address (https://twitter.com/EU_Commission/status/1280804957436948480) about the European Commission's hydrogen strategy (https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf), vice-president Timmermans emphasised that green hydrogen would be prioritised in Europe, but there would be temporary support for CCS production to "help us to replace dirty hydrogen".

The European Environmental Bureau described (https://eeb.org/europes-hydrogen-strategy-a-gift-to-fossil-fuel-companies-ngo-response/) the commission's su (https://www.eni.com/en-IT/low-carbon/hydrogen-europe-turns-blue.html)p (https://www.eni.com/en-IT/low-carbon/hydrogen-europe-turns-blue.html)port (https://www.eni.com/en-IT/low-carbon/hydrogen-europe-turns-blue.html) for blue hydrogen as a "gift to the fossil fuel industry".

While the commission's own analysis (https://ec.europa.eu/clima/sites/clima/files/docs/pages/com_2018_733_analysis_in_support_en_0.pdf) supports Timmerman's comments, it also mentions one of the key issues with retaining blue hydrogen:

> "In the decarbonised future, hydrogen obtained from electrolysis using decarbonised electricity is the preferable option, including 'green' hydrogen obtained from renewables. 'Blue' hydrogen obtained from steam reforming of natural gas coupled with CCS may also play a role, provided the inherent constraints of CCS are lifted."

These "inherent constraints" are highlighted by the International Renewable Energy Agency (https://www.irena.org/) (IRENA), which notes (https://irena.org/publications/2019/Sep/Hydrogen-A-renewable-energy-perspective) in its hydrogen report that CCS technology is not currently reaching its potential, remaining "off track in both power generation and industry".

It also states that blue hydrogen is "not inherently carbon free", given that CCS generally on (https://www.ipcc.ch/site/assets/uploads/2018/03/srccs_wholereport-1.pdf)l (https://www.ipcc.ch/site/assets/uploads/2018/03/srccs_wholereport-1.pdf)y cuts (https://www.ipcc.ch/site/assets/uploads/2018/03/srccs_wholereport-1.pdf) CO_2 emissions by 80-90%.

Higher carbon capture rates exceeding 90% are possible according to (https://www.iea.org/reports/the-future-of-hydrogen) the IEA, especially if an alternative hydrogen production method termed autothermal reforming (https://www.engineering-airliquide.com/autothermal-reforming-atr-syngas-generation) is used instead of the mc conventional steam methane reforming.

Nevertheless, blue hydrogen will not be zero-carbon – even at a 100% capture rate – because of emissions during methane production. Thomas Blank (https://rmi.org/people/thomas-koch-blank/) from the Rocky Mountain Institute tells Carbon Brief:

> "In the nascent discussions around hydrogen, I think it's been assumed that blue hydrogen is zero carbon – like there was an assumption for biofuels – and it's just not a zero-carbon fuel."

He notes that while high carbon capture rates can be achieved (https://twitter.com/philipsargent/status/1237487612992110605), this makes the process more expensive. "I think policymakers are starting to wake up to that reality," he says.

A net-zero report (https://es.catapult.org.uk/wp-content/uploads/2020/03/ESC_Innovating_to_Net_Zero_report_FINAL.pdf) by the UK's Energy Systems Catapult (https://es.catapult.org.uk/) states that while "speculative innovation measures" that result in 99% carbon capture would make blue hydrogen "highly appealing", anything less would effectively rule it out:

> "Without speculative innovation measures, methane reforming at a 95% capture rate is too high carbon to meet net-zero."

The IEA chart below shows the emissions that still arise from the use of fossil fuels with CCS, compared to electrolysis driven by renewables or nuclear power.

CO_2 intensity of hydrogen production using different methods. This includes electrolysis (blue) using different sources of electricity, as well as producing hydrogen directly from fossil gas (yellow) and coal (grey). Source: IEA.

However, this chart only shows CO_2 intensity. It does not account for upstream methane emissions resulting from leakages in the gas production and distribution system, which would not necessarily be avoided even if CCS were able to capture 100% of the CO_2 released by the process.

Gniewomir Flis of Agora Energiewende tells Carbon Brief that when considering blue hydrogen he is "very concerned" about these emissions.

"No publication to my knowledge – the IEA or others – accounts for these upstream emissions reliably," he says.

AukeHoekstra
@AukeHoekstra

I regularly hear blue hydrogen (natural gas steam reforming + CCS) emits just as little CO2 as green hydrogen (electrolysis). But you have to include the upstream emissions of natural gas production and then the emissions of blue hydrogen become significantly larger.

> **Julio Friedmann** @CarbonWrangler
> Replying to @CarbonWrangler
> 7/9 Today, the best answer in most markets is zero-C "blue" H2 from gas (#CCS). @SeanCasten is correct that you lose some efficiency in conversion. You also lose the carbon (!) that's the job.
>
> We could reduce today's H2 emissions about 400Mt/y this way, scaling fast & cheap

8:23 AM · Aug 7, 2020

118 · 50 people are Tweeting about this

Upstream emissions could significantly alter the climate impact of blue hydrogen, as highlighted in a report (https://www.pembina.org/reports/hydrogen-climate-primer-2020.pdf) which accounts for these leakages, by the Pembina Institute (https://www.pembina.org/) thinktank. It focuses on Canada, where plans are underway (https://www.petroleum-economist.com/articles/low-carbon-energy/energy-transition/2020/canada-to-announce-blue-hydrogen-blueprint) to ramp up blue hydrogen production in the fossil fuel-rich province of Alberta.

It estimates a range of 2.3-4.1kgCO2e per kg for blue hydrogen, which the report says reflects the variation in upstream methane emissions seen across the country.

The CCC's net-zero technical report (https://www.theccc.org.uk/wp-content/uploads/2019/05/Net-Zero-Technical-report-CCC.pdf) for the UK says that low-carbon hydrogen could be produced from fossil gas with emissions of around 0.3kgCO2 per kg, with a 95% capture rate. By comparison, the IEA estimates 0.9kgCO2 per kg of hydrogen with a 90% capture rate, as shown in the chart above.

However, when upstream emissions from fossil gas production are included, the committee says the emissions would be around 0.7-2.5kgCO2e per kg of hydrogen, at a rate of 95% capture.

To put this in context, BNEF's "new energy scenario" envisages 800m tonnes of global hydrogen use in 2050. If all of this were to be made from blue hydrogen at a 95% capture rate, it would be associated with lifecycle emissions of 600-2,000m tonnes of CO2 equivalent.

Dr David Joffe, the CCC's head of carbon budgets, tells Carbon Brief that there is room for some blue hydrogen within the UK's net-zero target, but not the very large quantities that would be required to meet all potential demand in large-scale sectors, such as heating and transport. He says:

> "There is no specific threshold beyond which it is definitely not OK…[But] as you get closer to net-zero, those residual emissions really start to matter."

Finally, there is also evidence that hydrogen released into the atmosphere from infrastructure leakages could have direct impact on climate change.

A report (https://www.gov.uk/government/publications/atmospheric-impacts-of-hydrogen-literature-review) prepared for the UK government noted that while hydrogen is not a pollutant by itself it can act as an "indirect greenhouse gas" by speeding up the accumulation of methane and ozone in the lower atmosphere.

According to the report, the one model study that has evaluated the global warming potential (https://www.carbonbrief.org/guest-post-a-new-way-to-assess-global-warming-potential-of-short-lived-pollutants) of hydrogen arrived at a value of 4.3. It concluded that while the climate impact of hydrogen emissions is likely to be small, the issue merits further examination.

How much is low-carbon hydrogen going to cost?

The role that green and blue hydrogen will play in decarbonising the economy will largely depend on how much both of them cost.

Not only do these forms of "low-carbon" hydrogen have to compete with each other and hydrogen derived from fossil fuels without the additional cost of CCS, they also need to contend with other alternative energy solutions, from electric vehicles to biofuels.

While the cost of producing hydrogen is an important component, it is not the only factor contributing to the final price paid by consumers.

The cost of transportation can be a significant factor, particularly if the hydrogen is imported from overseas, as well as the cost of distributing the hydrogen within a nation. There are also the profits taken by companies, which are added onto the final price.

The IEA is forthright (https://www.iea.org/reports/the-future-of-hydrogen) about the uncertainty around this topic, noting that "the relative costs of producing hydrogen from different sources in different regions, and how they will compete in the future, are unclear".

As it currently stands, grey hydrogen is the cheapest option, costing around $1/kg – if sourced from Middle East gas, but going as high as $3/kg in some regions. For China and India, both of which import most of their gas supplies, coal-based hydrogen tends to be the cheapest option.

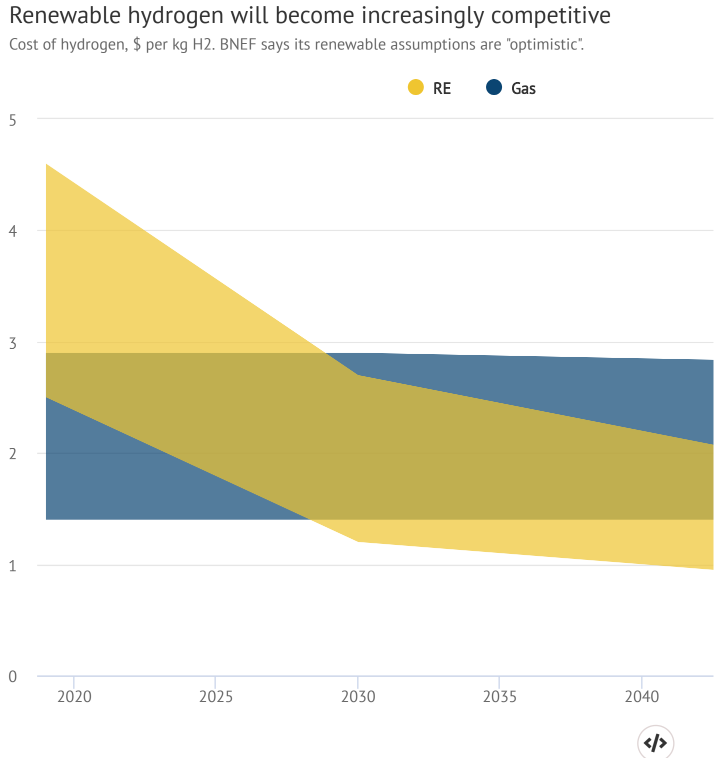
If CCS is used to turn the lowest-cost grey hydrogen blue, it brings costs to around $1.5/kg, according to the IEA.

By comparison, the agency states that green hydrogen generated using solar power or onshore wind is generally between $2.5 and $6/kg. (Others make lower estimates, see below.)

While hydrogen from some renewable sources may already (https://www.carbonbrief.org/renewable-hydrogen-already-cost-competative-say-researchers) be cost-competitive in certain applications, it still has a long way to go before it edges out its fossil fuel-derived equivalents.

Nevertheless, there is widespread optimism about green hydrogen's ability to compete, with the falling costs of renewable electricity frequently cited as the key driver.

The chart below shows that under "optimistic" assumptions by BNEF, the cheapest renewable hydrogen could outcompete even the cheapest low-carbon hydrogen from gas by 2030.



Projected future ranges of hydrogen costs, $/kg, up to 2050 for green hydrogen made using renewable electricity (yellow) and low-carbon hydrogen made using gas with carbon capture and storage (blue). Source: BNEF (https://data.bloomberglp.com/professional/sites/24/BNEF-Hydrogen-Economy-Outlook-Key-Messages-30-Mar-2020.pdf). Chart by Joe Goodman for Carbon Brief using Highcharts (https://www.highcharts.com/).

For many (https://www.bbc.com/future/article/20201112-the-green-hydrogen-revolution-in-renewable-energy), reports of record-low prices for solar power from Saudi Arabia (https://www.forbes.com/sites/dominicdudley/2019/10/17/cheapest-solar-energy-in-the-world/?sh=4a93ef204772#586333047727) to Portugal (https://www.pv-magazine.com/2020/08/27/portuguese-government-confirms-world-record-solar-price-of-0-01316-kwh/) in recent months support the idea that, despite its low efficiency and potentially high transport costs, green hydrogen imports could become a cost-effective solution for much of the world.

Another key factor is the rollout of electrolysers used to produce the green hydrogen, which have already fallen in price by 60% over the past decade. According to (https://ec.europa.eu/commission/presscorner/detail/en/QANDA_20_1257) the European Commission, prices "are expected to halve in 2030 compared to today with economies of scale".

In China, where such an economy of scale has already been achieved for alkaline electrolysers, production costs are already 80% lower than in Europe and North America, according to (https://data.bloomberglp.com/professional/sites/24/BNEF-Hydrogen-Economy-Outlook-Key-Messages-30-Mar-

2020.pdf) BNEF. European producers hope (https://www.euractiv.com/section/energy/news/europe-china-battle-for-global-supremacy-on-electrolyser-manufacturing/) to do the same for "innovative" newer electrolyser models.

A report (https://hydrogencouncil.com/wp-content/uploads/2020/01/Path-to-Hydrogen-Competitiveness_Full-Study-1.pdf) by industry group the Hydrogen Council concludes that "low-carbon" hydrogen, including both green and blue, would be competitive in 22 hydrogen applications comprising around 15% of global energy consumption by 2030.

Meanwhile, the International Renewable Energy Agency (https://www.irena.org/) (IRENA) has asserted (https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Sep/IRENA_Hydrogen_2019.pdf) that "future costs of green hydrogen will be below those for blue hydrogen fossil fuels". It says that hydrogen from low-cost renewables will be comparable with blue hydrogen from fossil fuels within five years.

Despite its acknowledged uncertainty, the IEA states that the cost of green hydrogen is on a clear downwards trajectory and could fall 30% by 2030 "as a result of declining costs of renewables and the scaling up of hydrogen production".

An assessment of recent cost studies by Dr Jan Rosenow from the Regulatory Assistance Project (https://www.raponline.org/)shows the range of estimates that have been made for green hydrogen, with most centring around $2 to $4/kg.

Jan Rosenow
@janrosenow

What are the projected costs of hydrogen?

Here is my current work in progress review of recent cost studies. Big caveat: comparing studies is difficult as some only include cost of production whereas others include transport and distribution.

7:49 AM · Nov 16, 2020

27 See Jan Rosenow's other Tweets

There are several factors that can contribute to different outlooks for the cost of hydrogen production.

For example, as the chart below shows, the IEA's projections – represented by the blue bars – are generally more conservative than those of BNEF, shown in red.

Range of projected hydrogen costs, $/kg, in 2030 based on work by the IEA (blue, with central estimates darker) and BNEF (red). Source: IEA, BNEF. Chart by Joe Goodman for Carbon Brief using Highcharts (https://www.highcharts.com/).

The main difference between the IEA and BNEF figures for green hydrogen is the result of electrolyser installation cost estimates, which are twice as high in the IEA's forecasts, says Gniewomir Flis of Agora Energiewende, as well as slightly higher electricity price assumptions by the agency.

To make the investment in electrolysers worthwhile, there needs to be relatively cheap electricity available fairly consistently.

An issue with connecting electrolysers directly to variable renewables is that they will not operate all the time, leading to higher costs for the resulting hydrogen.

It may be (https://theicct.org/sites/default/files/publications/final_icct2020_assessment_of%20_hydrogen_production_costs%20v2.pd cheaper to connect them to the grid, where production will be constant, but the electricity costs will be higher and will include paying for the grid connection. Unless the grid is completely decarbonised, this would also mean the hydrogen could not be called "green".

Even if electricity is free, as in the case of "curtailed" electricity from renewables, there needs to be a considerable amount of usage to make the investment pay off. This is why building electrolysers to store curtailed power may not always make economic sense (See: "Electricity" below).

High electrolyser usage rates can help make the initial capital costs in hydrogen production worthwhile, although this has to be balanced against the cost of electricity as it is used.

Ultimately, fuel costs are expected to have the biggest impact on future hydrogen prices, meaning the most significant drivers of the relative success of green and blue hydrogen will be future electricity and gas costs.

A report (https://s3-eu-west-1.amazonaws.com/media.newore.catapult/app/uploads/2020/09/07105124/Solving-the-Integration-Challenge-ORE-Catapult.pdf) by the UK's Offshore Renewable Energy (ORE) Catapult (https://ore.catapult.org.uk/) on the potential of offshore wind to generate hydrogen estimated – based on "conservative assumptions" – that green hydrogen could be cheaper than blue hydrogen by 2050.

It then points to indicators that offshore wind and electrolyser costs could fall more rapidly than expected, noting that "decision-makers have been continually blind-sided by the unexpectedly rapid fall in the costs of wind and solar energy".

In that case, ORE says, green hydrogen could be cheaper than blue by 2030, "approximately 20 years ahead of our forecast".

Another big factor when considering the cost of hydrogen is transport, as moving the gas around is more challenging and expensive than moving methane.

Importing cheap hydrogen from sunny or windy regions is an appealing strategy that some nations are exploring (See: "How will hydrogen affect global geopolitics?" below).

However, these imports may end up not being particularly cheap, owing to the high costs of transporting hydrogen around the world in special containers at high pressures (https://energies.airliquide.com/resources-planet-hydrogen/how-hydrogen-stored) and low temperatures.

Flis tells Carbon Brief that using IEA estimates, or even using more optimistic transport cost assumptions from the Japanese research agency Nedo (https://eneken.ieej.or.jp/data/7944.pdf), imported hydrogen may struggle to compete with domestically sourced supplies.

For example, green hydrogen made in the UK might cost $3.20/kg in 2030, versus US$1.70/kg in Portugal and $1.30/kg in Saudi Arabia. But the cost of transporting the fuel – some $2.70-4/kg, according to the IEA – would mean the imported option remains more expensive.

Nevertheless, nations may require imported hydrogen if they lack sufficient renewable resources to generate enough on their own soil.

The cost of transport also depends (https://www.iea.org/reports/the-future-of-hydrogen) on the route. The cost of transporting hydrogen via pipelines increases rapidly with distance, whereas when using a ship the starting cost is much higher but remains relatively stable with increasing distances.

Transmission and distribution of hydrogen gas via pipeline is cheaper for distances up to around 1,500km, the IEA says. In early 2020, a group of European gas infrastructure companies came forward (https://gasforclimate2050.eu/sdm_downloads/european-hydrogen-backbone/) with a plan to connect the continent with a "backbone" of pipelines.

Gniewomir Flis
@gnievchenko

Replying to @gnievchenko

So the first takeaway is that hydrogen as an end product does not lend itself well to shipping.

What about pipelines? In July a group of European TSOs came out with their suggestion of an European Hydrogen Backbone.

11/18

6:39 AM · Sep 28, 2020

However, for longer distances it makes more economic sense to convert hydrogen into a "liquid carrier", such as ammonia. (For more on transporting hydrogen and ammonia, see: "Shipping and aviation" below.)

Finally, supply and demand can also have an impact on final price. A report (https://www.auroraer.com/wp-content/uploads/2020/08/Aurora-Hydrogen-in-the-Northwest-European-energy-system.pdf?eid=QWM0lO2pqSzW4FSRtxDWog%3D%3D#gf_29) by Aurora Energy Research (https://www.auroraer.com/) concluded that in a scenario with high hydrogen demand, green hydrogen is "significantly more expensive than blue".

In comparison, if demand is lower, the cost of a hydrogen rollout based primarily on green sources comes at "negligible extra cost".

How would hydrogen use affect global geopolitics?

For decades, the fossil fuels – and oil, in particular – have played (https://www.chathamhouse.org/sites/default/files/2019-08-14-FutureOilDemand.pdf) a critical role in international relations and driven many of the world's major conflicts.

In his 2002 book The Hydrogen Economy (https://books.google.co.uk/books/about/The_Hydrogen_Economy.html?id=Ax31qQwRIrwC&source=kp_book_description&redir_esc=y), social theorist Jeremy Rifkin (https://www.foet.org/) imagined a world in which the mass rollout of hydrogen put an end to this:

> "The road to global security lies in lessening our dependence on Middle East oil and making sure that all people on Earth have access to the energy they need to sustain life. The hydrogen economy is a promissory note for a safer world."

Rifkin's book came out at a time of great enthusiasm for hydrogen, but this was before the fracking boom (https://www.wsj.com/articles/a-decade-in-which-fracking-rocked-the-oil-world-11576630807), when it was thought (https://www.theguardian.com/books/2002/oct/12/highereducation.scienceandnature) US oil reserves would run dry within a decade and alternatives were urgently needed. (See: "Why is hydrogen being 'hyped' again now?")

Hydrogen is currently a very localised industry, with 85% (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7326412/) produced and used on site – in part, due to high transport costs. As most hydrogen is "grey", it is cheapest (https://www.iea.org/reports/the-future-of-hydrogen) in regions with low gas prices, such as the Middle East and North America.

In the "rapid" pathway of its latest energy outlook (https://www.carbonbrief.org/analysis-world-has-already-passed-peak-oil-bp-figures-reveal), BP says there is a growing role for electricity and hydrogen, adding: "These energy carriers are more costly to transport than traditional hydrocarbons causing energy markets to become more localised."

However, while Rifkin's optimism about hydrogen may have been premature, he is not alone (https://www.amazon.co.uk/Hydrogen-New-Oil-Thierry-LEPERCQ-ebook/dp/B07RFNW76P) in comparing hydrogen to oil and speculating about its impact on geopolitics. As one paper (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7326412/) published in June 2020 by Prof Thijs Van de Graaf (https://www.thijsvandegraaf.be/) of Ghent University (https://www.ugent.be/ps/politiekewetenschappen/giis/en) and colleagues titled "the new oil?" puts it:

> "Over time, cross-border maritime trade in hydrogen has the potential to fundamentally redraw the geography of global energy trade, create a new class of energy exporters, and reshape geopolitical relations and alliances between countries"

The expansion of green hydrogen has the potential to shift the existing balance of trade so that nations rich in solar and wind energy, such as Chile (https://www.ft.com/content/16481d72-1495-4b24-9c59-97ea9a856cc1), Australia and Morocco, become major exporters. The Economist (https://www.economist.com/briefing/2020/09/17/americas-domination-of-oil-and-gas-will-not-cow-china) has dubbed these future energy powerhouses "electrostates".

Prof Ad van Wijk (http://profadvanwijk.com/) of Delft University of Technology (https://www.tudelft.nl/en/) says that, while many of the nations planning to expand their hydrogen use would struggle to do so on their own soil, there will be more than enough renewable energy available worldwide.

As an example, he tells Carbon Brief that covering (http://profadvanwijk.com/green-gases-from-sun-and-wind-are-a-new-opportunity-for-north-africa/) around 8% of the Sahara Desert in solar panels could generate the entire global energy demand. "Of course, it takes time to build the solar and wind, but in the end there is no limit."

Lacking sufficient cheap renewables, he says European nations will, ultimately, turn to imports:

> "That is the same thing we do today. We import a lot of our energy, in Europe at least, from sites where you have cheap production of oil and gas or coal."

This is evident in existing hydrogen strategies, which show that prospective hydrogen leaders only see a fraction of their supply being produced locally.

In its strategy (https://www.bundesfinanzministerium.de/Content/DE/Standardartikel/Themen/Schlaglichter/Konjunkturpaket/2020-06-03-konjunkturpaket-beschlossen.html), Germany proposed a modest (https://twitter.com/gnievchenko/status/1310544553024327682) 14 terawatt-hours (TWh) of its 110TWh requirements for green hydrogen coming from within its borders by 2030. For this reason, Germany has also earmarked funds to support use of its electrolyser equipment overseas, to make hydrogen for use at home.

Limited international trade is already underway, with Japan recently receiving the "world's first (https://www.rechargenews.com/transition/-world-s-first-international-hydrogen-supply-chain-realised-between-brunei-and-japan/2-1-798398)" shipment of hydrogen from Brunei and Germany signing a deal (https://www.moroccoworldnews.com/2020/06/305441/morocco-first-to-partner-with-germany-to-develop-green-hydrogen-sector/) with Morocco to make use of its "ideal (https://www.cleanthinking.de/wasserstoffallianz-marokko-gruenes-gas-afrika/)" conditions for green hydrogen production.

Japanese and Australian ministers met earlier this year to agree (https://www.pv-magazine-australia.com/2020/01/24/australia-and-japan-agree-to-hydrogen-future/) on a future of hydrogen trade, to supply the resource-poor Asian nation with hydrogen. The Australian government has since backed (https://www.ft.com/content/73505b3c-acd8-4bd5-b91a-fddfa2f331fb) a AUS$53bn ($39bn) "Asian Renewable Energy Hub" that will contribute to this.

Germany is also looking (https://www.bloomberg.com/news/articles/2020-08-21/congo-hydrogen-plant-being-considered-by-european-turbine-makers?sref=Oz9Q3OZU) as far afield as the Democratic Republic of Congo, where a major hydropower site is being considered as a potential location for a hydrogen plant "add on". Such dealings have raised concerns (https://twitter.com/jonathangaventa/status/1296788916008357888) of a new dynamic alluded to by Van de Graaf and his collaborators:

"To the extent that developing countries are seen solely as the providers of raw materials, the hydrogen revolution carries a risk of 'green colonialism'."

Jonathan Gaventa
@jonathangaventa

Green hydrogen from DRC hydropower could be exported to Europe.

A sign that Africa can benefit from the hydrogen economy?

Or- as only 10% of Congolese have access to electricity- another example of resource extraction that leaves local citizens behind?

Congo Hydrogen Plant Being Considered by European Turbine Makers
bloomberg.com

7:39 AM · Aug 21, 2020

24 See Jonathan Gaventa’s other Tweets

The future of hydrogen trade – and the trade in hydrogen-derived fuels, such as ammonia – will be influenced by the cost of transporting them around the world (See: “How much is low-carbon hydrogen going to cost?”).

The IEA has stressed (https://www.iea.org/reports/the-future-of-hydrogen) the need for international shipping routes for hydrogen, stating that such trade “needs to start soon if it is to make an impact on the global energy system”. Van Wijk tells Carbon Brief that in Europe, at least, another key component will be expanding and retrofitting gas pipelines to transport hydrogen from Africa.

Others have warned (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7326412/) that the “slow and incomplete globalisation” of gas markets suggests the hydrogen trade may not take off as fast as some assume.

The Suiso Frontier, the first liquefied hydrogen carrier, at its launch ceremony. Credit: Agency for Natural Resources and Energy.

If the export market does ramp up, it will not guarantee the "safer world" proposed by Rifkin. A report (https://www.belfercenter.org/sites/default/files/files/publication/Geopolitical%20and%20Market%20Implications%20of% released in March 2020 by Harvard University's Belfer Center for Science and International Affairs (https://www.belfercenter.org/) concluded that rather than disrupting the "hegemony" of oil-rich nations, a green hydrogen economy may play out in a similar way to the existing fossil fuel-based one:

> "Future market dynamics will likely resemble today's regional natural gas markets – with corresponding potential for geopolitical conflict".

In an article for Foreign Policy (https://foreignpolicy.com/2020/10/05/climate-geopolitics-petrostates-russia-china/), published in October 2020, Prof Jason Bordoff (https://www.sipa.columbia.edu/faculty-research/faculty-directory/jason-bordoff), a former senior director at the US National Security Council, described the risks that could face seaborne trade in hydrogen and ammonia.

He said, in addition, that nations such as Saudi Arabia and Russia may be among those that end up dominating the market. Saudi energy minister Prince Abdulaziz bin Salman recently outlined (https://www.bloomberg.com/news/articles/2020-11-18/biggest-in-oil-saudis-aim-next-to-be-largest-hydrogen-exporter?sref=Oz9Q3OZU) his plans to ensure the nation is the "biggest exporter of hydrogen on earth".

"To defy the conventional wisdom…consider that some of today's petrostates may be tomorrow's electrostates," Bordoff wrote.

How could hydrogen help different sectors reach net-zero?

In theory, hydrogen has the potential to decarbonise everything from the steel used to make someone's car to the g heating their home.

However, in practice, hydrogen is unlikely to be taken up universally. Moreover, the volume required to satisfy all the possible applications for low-carbon hydrogen would likely far exceed the amount available, even if production is significantly scaled up.

This section breaks down how hydrogen could be applied in transport, industry, heating and the power sector to help them achieve net-zero emissions.

Transport

The focus on using hydrogen as an alternative to fossil fuels in transport has a history dating back to the earliest waves of enthusiasm, when it was promoted as an alternative to oil.

This is evident (https://www.iea.org/reports/the-future-of-hydrogen) from the policies that have been brought in to support hydrogen, which are predominantly directed at cars, refuelling stations and buses.

Nevertheless, mobility is currently the smallest (https://www.woodmac.com/press-releases/green-hydrogen-cost-to-halve-by-2030---a-boost-to-south-koreas-hydrogen-ambitions/) component in the entire hydrogen market, representing less than 0.1% of global demand.

There is enthusiasm (https://www.nature.com/articles/s41558-020-0891-0) from many industry actors for hydrogen to succeed in the transport sector and it is already being applied in some niche markets. For example, around 25,000 forklift trucks are now powered (https://fuelcellsworks.com/news/hydrogen-drives-clean-forklifts/) using hydrogen.

However, the rise of battery electric cars means they are widely viewed as the vehicles of a net-zero future. The UK's Climate Change Committee (https://www.theccc.org.uk/) concluded (https://www.theccc.org.uk/wp-content/uploads/2018/11/Hydrogen-in-a-low-carbon-economy.pdf) in 2018 that electric vehicles are "now well placed to deliver the bulk of decarbonisation for cars and vans".

Hydrogen may still have a significant role to play for transport that is harder to decarbonise, from long-distance trucks to planes, but progress in many of these sectors is still in its early days.

Road transport

As of 2019, there were just (https://www.iea.org/reports/the-future-of-hydrogen) 11,200 passenger vehicles running on hydrogen fuel cells in operation, mostly in California, Europe and Japan. As a comparison, the global battery electric car fleet exceeds 7m (https://www.iea.org/reports/global-ev-outlook-2020), after reaching the first million (https://www.carbonbrief.org/iea-there-are-now-more-than-one-million-electric-cars-on-the-worlds-roads) just five years ago.

The hydrogen fuel cell vehicle industry has been limited by a "chicken-and-egg (https://royalsocietypublishing.org/doi/pdf/10.1098/rsta.2016.0400)" problem. Not enough cars have been produced to bring prices down and the lack of demand means hydrogen refuelling stations, which are expensive, have not been widely installed. This, in turn, has helped limit demand.

A recent Hydrogen Council report (https://hydrogencouncil.com/wp-content/uploads/2020/01/Path-to-Hydrogen-Competitiveness_Full-Study-1.pdf) concluded that a "radical" increase in production to around 1m cars each year will be necessary to make fuel-cell vehicles competitive.

Meanwhile, electric cars, which were very expensive during the early days of fuel-cell vehicles, have seen costs drop considerably and extensive charging infrastructure rolled out.

The hydrogen-powered Toyota Mirai costs (https://www.autocar.co.uk/car-review/toyota/mirai) £66,000 ($88,015), compared to the battery electric Tesla Model 3 at around (https://www.autocar.co.uk/car-review/tesla/model-3) £45,000 ($60,010), or a medium-sized conventional UK car which tends (https://www.nimblefins.co.uk/average-cost-cars-uk#:~:text=We%20looked%20at%20on%2Dthe,%C2%A322%2C000%20to%20%C2%A336%2C000.) to fall in the range of £22,000-£36,000 ($29,338-48,008).

Hydrogen fuel cells have some vocal detractors, with the outspoken Tesla chief executive Elon Musk calling them (https://www.cnbc.com/2019/02/21/musk-calls-hydrogen-fuel-cells-stupid-but-tech-may-threaten-tesla.html) "fool cells" and dismissing the technology as "mind-bogglingly stupid".

Prof Ferdinand Dudenhöffer (https://www.cleanenergywire.org/experts/dudenhoffer), director at the University of Duisburg-Essen's Centre for Automotive Research (https://www.uni-due.de/car/index_en.php), tells Carbon Brief he has always been sceptical about hydrogen cars:

> "I don't believe in hydrogen and fuel-cell vehicles as passenger cars at all, because the technology is very cost intensive…If you want to sell a car for €30,000 or so it makes no sense to increase the price very sharply by [using] fuel cell technologies."

While there have been attempts to get fuel-cell vehicles into the mass market, Dudenhöffer says it is now widely accepted this is unlikely to happen.

This year, Mercedes-Benz has cancelled (https://electrek.co/2020/04/22/daimler-ends-hydrogen-car-development-because-its-too-costly/) its fuel-cell programme after three decades due to high costs and Volkswagen has published a statement (https://www.volkswagen-newsroom.com/en/stories/battery-or-fuel-cell-that-is-the-question-5868) concluding: "Everything speaks in favour of the battery and practically nothing speaks in favour of hydrogen".

Prof Jenny Nelson (https://www.imperial.ac.uk/people/jenny.nelson) of Imperial College London, who co-authored a recent European Academies' Science Advisory Council (https://easac.eu/) (EASAC) commentary (https://easac.eu/publications/details/hydrogen-and-synthetic-fuels/) on the subject, tells Carbon Brief that transport is a good example of hydrogen being an inefficient use of renewable energy:

> "It will require approximately 2.5 times as much electricity to run the same vehicle with renewable hydrogen and fuel cells as it would with batteries, and about five times as much electricity to run the same vehicle with synthetic fuels made from renewable hydrogen."

However, hydrogen analyst Gniewomir Flis says there is still a lot of interest in making a success out of this technology:

> "So much money was sunk into it over the years and it would be quite embarrassing to admit that after all these years battery electric vehicles are just a better solution."

Japan has announced (https://www.meti.go.jp/english/press/2019/pdf/0312_002b.pdf) plans to get 800,000 hydrogen fuel cell vehicles onto its roads by 2030 and South Korea says (http://www.koreaherald.com/view.php?ud=20190117000468) it will go even higher with 1.8m.

Fuel cells do have advantages over batteries, not least their far shorter refuelling times. Some have (https://www.npr.org/2019/03/18/700877189/japan-is-betting-big-on-the-future-of-hydrogen-cars) suggested that people living in dense East Asian cities are less likely to have space to charge an electric car overnight and will instead opt for hydrogen.

Japanese and Korean car manufacturers Toyota and Hyundai have announced ambitious plans (https://www.prnewswire.com/news-releases/hyundai-motor-group-reveals-fcev-vision-2030-300763580.html) to scale up their production. Toyota recently launched (https://www.marketwatch.com/story/the-new-awd-electric-polestar-2-is-a-good-blend-of-performance-and-efficiency-2020-09-09) a new version of its Mirai (https://www.toyota.co.uk/new-cars/new-mirai/meet-mirai#1) – the Japanese word for "future" – despite low sales (https://eu.usatoday.com/story/money/2019/12/26/worst-selling-cars-of-the-decade/40768373/) of the previous model.

Toyota Mirai (2nd gen concept). Credit: Toyota

However, there are signs (https://twitter.com/MLiebreich/status/1279713400881373184) that even these industry leaders are undergoing "u-turns (https://www.aljazeera.com/economy/2020/7/28/hyundais-hydrogen-u-turn-now-it-wants-electric-supremacy)", as they reveal plans to ramp up their production of battery electric vehicles.

Toyota has plans (https://uk.reuters.com/article/us-toyota-electric-idUKKBN26K0VL) to scale up global sales of electric and hybrid cars to 5.5m in 2025, while sales of hydrogen cars remain in the tens of thousands.

Jon Hunt (https://uk.linkedin.com/in/jon-hunt-8469b02b), manager of alternative fuels at Toyota (https://www.toyota.co.uk/?gclid=Cj0KCQjw28T8BRDbARIsAEOMBcz_EV4b8CRB0Eo0nppRHvH5QIPTC0LVRBu1MnFn6RwgEMtj--nmLtIaAvFhEALw_wcB&gclsrc=aw.ds), tells Carbon Brief that while they are also pushing electric vehicles they, ultimately, see fuel-cell cars being "as attainable as hybrids".

Hunt says that as production scales up, prices will drop. He also emphasises that while batteries are expensive and have limited lifetimes, the fuel stacks in hydrogen cars "will keep running and running", meaning they can be re-sold.

Crucially, he also notes that the Mirai's fuel stack (https://afdc.energy.gov/vehicles/how-do-fuel-cell-electric-cars-work) (the assembly of fuel cells that use hydrogen and oxygen to produce electricity) is around twice as powerful as it needs to be. This makes it more expensive, but provides an insight into Toyota's motivation, he says:

> "The reason for doing that is that you standardise the unit and that unit that goes into the Mirai can be used in trucks, as we are doing, or in buses as we are doing, or in ships as we are doing, and it doesn't need to be changed very much."

The fate of fuel-cell cars is, to some extent, wrapped up with larger road vehicles, where there could be greater demand for hydrogen.

For regular buses, electric vehicles are already dominating the transition away from fossil fuels. According to thinktank Carbon Tracker (https://carbontracker.org/reports/nothing-to-lose-but-your-chains/), 59% of bus sales in China last year were electric.

However, for heavy-duty trucks and intercity coaches that have high power demands and need to cover long distances, direct electrification using batteries is more challenging. Fuel cells may, therefore, have a competitive advantage for these vehicles.

Hunt tells Carbon Brief that for these applications to succeed, particularly for commercial vehicles, the technology must be demonstrated "beyond doubt". "You can't just turn up to [haulage company] Eddie Stobart and say 'look, can you just throw a couple of fuel-cell trucks on to haul around your goods, just to try it," he says:

> "The strategy is, get cars on the road because cars are quite an easy market to penetrate… we know that we can sell enough of those cars to specific users to demonstrate the technology works and help the infrastructure get developed."

However, even though heavy-duty vehicles are a significant source of emissions and also a "hard-to-decarbonise" sector, the switch to fuel cells is not a foregone conclusion.

Patrik Akerman (https://europeanroadconference2018.sched.com/speaker/benjamin_wickert.1y4s6pea), head of business development at Siemens eHighway, sees these vehicles as a "risky bet", if you assume battery electric cars have "won the race against fuel-cell cars".

He tells Carbon Brief that if you "take the word of Hyundai and others", then the size of the market for fuel cells will be too small to achieve economies of scale within trucks alone:

"Then that means that, not only will the fuel be too expensive for trucks, but also the vehicles will never come down in price to be competitive."

According to (https://data.bloomberglp.com/professional/sites/24/BNEF-Hydrogen-Economy-Outlook-Key-Messages-30-Mar-2020.pdf) BloombergNEF, while hydrogen could still have a role for long-haul trucks, the bulk of the future bus, light truck and car market will likely be electric and getting a fuel-cell industry off the ground would require $105bn in subsidies by 2030.

The clear alternative, according to Akerman, is to install overhead charging cables of the type his company is already trialling (https://www.businessinsider.com/germany-opens-first-e-highway-trucks-overhead-cables-2019-5?r=US&IR=T) in Germany.

A literature review (https://www.sciencedirect.com/science/article/pii/S2352484719301167?via%3Dihub) of research into climate-friendly trucking found virtually every study that included these "catenary" wires concluded this was the preferable decarbonisation technology, outperforming hydrogen fuel cells.

The chart below, from a white paper by the International Council on Clean Transportation (https://theicct.org/) (ICCT), demonstrates that hydrogen fuel cells, represented by purple bars, are more expensive than catenary wires, as well as other alternatives to conventional fossil fuels for trucks in Germany.

Additional cost for four different emissions reduction scenarios compared to a reference case based on fossil fuel use for the long-haul, heavy-duty freight transport sector in Germany. Source: ICCT (https://theicct.org/sites/default/files/publications/Zero-emission-freight-trucks_ICCT-white-paper_26092017_vF.pdf), based on Kasten et al. (2016) (https://www.umweltbundesamt.de/sites/default/files/medien/377/publikationen/2016-11-10_endbericht_energieversorgung_des_verkehrs_2050_final.pdf).

There is also potential (https://www.elaad.nl/news/auke-hoekstra-electric-trucks-economically-and-environmentally-desirable-but-misunderstood/) for the development of electric trucks that do not rely on catenary wires, which may be feasible despite concerns (https://twitter.com/AukeHoekstra/status/1253989076698628099) about the size and weight of batteries required.

Auke Hoekstra (https://www.edx.org/bio/auke-hoekstra), a senior advisor in smart mobility at the Eindhoven University of Technology (https://www.tue.nl/en/), found that in a scenario comparing its costs to other options from an IEA report (https://www.iea.org/reports/the-future-of-trucks) on trucking, the electric truck came out on top.

AukeHoekstra
@AukeHoekstra

Replying to @AukeHoekstra

I added the scenario of an electric truck with 400 km range. I found it blew diesel and hydrogen out of the water with very little downsides. (Catenary is great too but requires international institutional cooperation: I'm not holding my breath.)
elaad.nl/news/auke-hoek...

5:07 AM · Apr 25, 2020

A key problem is the ever-present question of low-carbon hydrogen availability. According to (https://www.iea.org/reports/the-future-of-hydrogen) the IEA, if every car, truck and bus currently in operation was replaced with a fuel-cell vehicle, hydrogen demand could reach 300Mt each year, more than four times current levels for all uses.

With low-carbon hydrogen likely to be in limited supply and demand set to continue rising as vehicle ownership increases, Akerman tells Carbon Brief that, wherever possible, it is better to electrify:

> "[Siemens makes] the electrolysers [for hydrogen]. We are very happy to supply this to the market, but we see that this is a massive undertaking just to handle the existing demand."

He adds that there are some sectors, such as long-haul shipping, which are unlikely to switch to batteries, making their need for green hydrogen even greater. "Anything where you can [directly] use electricity…you should," he concludes.

Shipping and aviation

Aviation and shipping are responsible for around 5% (https://www.transportenvironment.org/sites/te/files/publications/Shipping%20and%20aviation%20emissions%20and%2(6.pdf) of global emissions and are also difficult to electrify. Hydrogen or hydrogen-based fuels, such as ammonia (https://royalsociety.org/-/media/policy/projects/green-ammonia/green-ammonia-policy-briefing.pdf), could, therefore, be crucial for net-zero goals.

The past year has seen Japan launch (https://www.ft.com/content/8ae16d5e-1bd4-11ea-97df-cc63de1d73f4) the first ocean-going liquid hydrogen carrier ship, dubbed Hydrogen Frontier, and seen the first (https://www.zeroavia.com/press-release-25-09-2020) hydrogen-powered small passenger plane take flight.

However, these demonstration projects, both of which used hydrogen ultimately (https://www.ft.com/content/8ae16d5e-1bd4-11ea-97df-cc63de1d73f4) derived (https://www.newscientist.com/article/2255751-zero-emissions-hydrogen-plane-test-was-part-powered-by-fossil-fuels/) from fossil fuels, are currently the upper limit of hydrogen's progress in these sectors.

A hydrogen-powered Piper Malibu made a first flight from Cranfield Airport in the UK to launch ZeroAvia's efforts to achieve service entry by the end of 2023. Credit: ZeroAvia.

Xiaoli Mao (https://theicct.org/staff/xiaoli-mao), a maritime researcher at the International Council on Clean Transportation (https://theicct.org/) (ICCT), tells Carbon Brief she thinks it is unlikely shipping will decarbonise without hydrogen, but there are barriers preventing it from replacing fossil fuels:

> "The industry has said that hydrogen is one of the main options they are interested in pursuing, but without dedicated funding, not much is happening."

To reach the International Maritime Organization's (https://www.imo.org/en) (IMO) target (https://www.imo.org/en/MediaCentre/PressBriefings/Pages/06GHGinitialstrategy.aspx) of a sector-wide 50% emissions cut by 2050 compared to 2008, industry figures have agreed (https://www.globalmaritimeforum.org/getting-to-zero-coalition) that commercially viable zero-emission vessels must enter the global fleet by 2030.

Yet, despite various early-stage projects (https://www.globalmaritimeforum.org/news/mapping-of-zero-emission-pilots-and-demonstration-projects/) using hydrogen-based fuels in shipping, this capital-intensive industry is gripped by "deadlock", according to a report (https://www.shell.com/promos/energy-and-innovation/decarbonising-shipping-all-hands-on-deck/_jcr_content.stream/1594141914406/b4878c899602611f78d36655ebff06307e49d0f8/decarbonising-shipping-report.pdf) by Shell.

Another report by maritime organisation Lloyds Register (https://www.lr.org/en-gb/marine-shipping/) concluded in 2019 that "there is still uncertainty when choosing one fuel, one technology and one route".

Hydrogen in ships could be either burned in engines or used to generate electricity in fuel cells, but both options would require expensive new infrastructure to transport and store the gas on ships.

Hydrogen requires (https://www.iea.org/reports/the-future-of-hydrogen) at least five times more storage volume than oil-based fuels and there are concerns (https://www.reuters.com/article/shipping-energy-hydrogen/focus-first-wave-of-ships-explore-green-hydrogen-as-route-to-net-zero-idINL8N2H45GR) it could eat into cargo storage and, therefore, profits.

However, Mao conducted a modelling study (https://theicct.org/publications/zero-emission-container-corridor-hydrogen-2020) earlier this year that found 99% of the container ships travelling the busy route between China and the US could be powered by hydrogen "with only minor changes to fuel capacity or operations".

Nevertheless, Ole Graa Jakobsen (https://www.linkedin.com/in/ole-graa-jakobsen/?originalSubdomain=dk), head of fleet technology at the world's largest container shipping firm Maersk, tells Carbon Brief that, while it could have uses in smaller vessels like ferries, they "do not expect hydrogen to be a relevant fuel" for their ships.

"We…believe (https://shippingwatch.com/regulation/article12490208.ece) that it will make more sense to convert hydrogen to methanol or ammonia and use this as a fuel," he says.

While it still requires more space than fossil fuels, ammonia is more energy dense than hydrogen and is already transported around the world on ships. Methanol, too, is being considered (https://www.stenabulk.com/press-and-news/press-releases/proman-stena-bulk-promote-greener-shipping-future-additional-methanol) as a more practical alternative to hydrogen.

As the chart below shows, in long-distance shipping, ammonia in particular is likely to be cheaper than hydrogen, largely due to lower storage costs (shown in green). While hydrogen is difficult to liquify, ammonia is easily stored as a liquid at modest pressures and temperatures.

Current and future cost of different fuel and powertrain alternatives in large carrier ships, including the fossil fuel options of very low sulphur fuel oil (VLSFO) and liquefied natural gas (LNG), as well as internal combustion engines (ICE) powered by hydrogen and ammonia. Source: IEA (https://www.iea.org/reports/the-future-of-hydrogen).

Like hydrogen, both ammonia and methanol can be low-carbon, but most of the current demand is supplied by fossil fuels (See: “Industry”).

A report (https://www.shell.com/promos/energy-and-innovation/decarbonising-shipping-all-hands-on-deck/_jcr_content.stream/1594141914406/b4878c899602611f78d36655ebff06307e49d0f8/decarbonising-shipping-report.pdf) released in September 2020 by Shell based on interviews with 80 industry figures identified green hydrogen and ammonia as popular options for decarbonising shipping with 65% and 55% of respondents saying they saw them as part of the future mix. Methanol was “rarely mentioned”, with only 10% saying they saw it as important for the future.

However, the report also concluded that there is “little evidence” that other industries consider ammonia as a future fuel:

> “For that reason, if shipping was to select ammonia as its dominant fuel, it is likely that the infrastructure costs would be borne entirely by this sector.”

Ultimately, mandates requiring ships to cut emissions, effective carbon pricing and low-carbon fuel standards are among proposals that will likely be required to make these alternatives competitive.

Aviation is another difficult industry to decarbonise and one for which hydrogen could have a pivotal role, says Dr Ahmad Baroutaji (https://www.wlv.ac.uk/about-us/our-staff/ahmad-baroutaji/), an engineer at the University of Wolverhampton (https://www.wlv.ac.uk/) who published an overview (https://www.sciencedirect.com/science/article/abs/pii/S1364032119301157) of this topic last year. He tells Carbon Brief:

> “The aviation industry has a target (https://www.iata.org/en/programs/environment/climate-change/) of achieving a 50% reduction in net CO_2 emissions by 2050 compared to 2005 levels and such an ambitious target is only possible via deploying more hydrogen technologies into the sector.”

The gas could be directly combusted, used to power fuel cells or combined with CO_2 to create liquid synthetic fuels similar to kerosene, which would require relatively few changes in existing infrastructure.

One issue with hydrogen use in planes is the water vapour it produces when combusted, given water's contribution (https://www.carbonbrief.org/guest-post-calculating-the-true-climate-impact-of-aviation-emissions) to the greenhouse effect at high altitudes.

This issue led to the UK's Climate Change Committee (https://www.theccc.org.uk/) dismissing this option altogether, stating (https://www.theccc.org.uk/publication/hydrogen-in-a-low-carbon-economy/) in 2018 "there does not therefore appear to be a role for hydrogen in decarbonising aviation".

Recent assessments have been more positive. A report (https://www.fch.europa.eu/sites/default/files/FCH%20Docs/20200507_Hydrogen%20Powered%20Aviation%20report_FIN for the European Commission in May proposed targets of 2035 and 2040 for the introduction of hydrogen-powered short- and medium-range flights, which in total cause two thirds of current aircraft emissions.

The same report concluded that hydrogen combustion could cut each flight's overall climate impact by 50-75%, accounting for non-CO2 impacts (https://www.carbonbrief.org/guest-post-calculating-the-true-climate-impact-of-aviation-emissions) including water vapour, soot and nitrogen oxides (NOx) as well. Fuel-cell propulsion would have an even larger benefit of between 75-90%.

According to the report, hydrogen fuel cells produce water vapour that is cool enough to capture and store on the plane, therefore avoiding the climate impact. While this is not possible for hydrogen combustion, its climate impact is still lower than kerosene.

Baroutaji says that despite fuel cells' promise and use in test flights they are still "only suitable for powering light and small aircraft". Nevertheless, he says there is considerable industry interest in hydrogen technology.

Airbus has released (https://www.airbus.com/newsroom/press-releases/en/2020/09/airbus-reveals-new-zeroemission-concept-aircraft.html) three concepts for the "world's first zero-emission commercial aircraft", which the company wants to enter service by 2035. The planes would rely on hydrogen combustion with some support from hydrogen fuel cells.

ZEROe Airbus concept aircraft. Credit: Airbus

Following the launch of Airbus' 2035 target, Boeing product developer Michael Sinnett said he did not think hydrogen flight is "something that's right around the corner", according to aviation website FlightGlobal (https://www.flightglobal.com/airframers/hydrogen-powered-airliners-unlikely-in-near-term-boeing-exec/140273.article).

Although Boeing itself launched (https://www.thetimes.co.uk/article/boeing-tests-first-hydrogen-powered-plane-bwlfbjf6wrh) the first-ever hydrogen aircraft in 2008, Sinnett cited limits to hydrogen production and storage as barriers for commercial applications. Liquified hydrogen would need (https://www.mckinsey.com/industries/travel-logistics-and-transport-infrastructure/our-insights/how-airlines-can-chart-a-path-to-zero-carbon-flying) four times the storage volume of kerosene.

In the shorter term, companies may use (https://insideclimatenews.org/news/26102020/hydrogen-fueled-aircraft-clean-energy-emissions) synthetic fuels made from hydrogen and CO2 to replace kerosene, despite high production costs. They would also have the major drawback of emitting CO2.

However, if the CO2 used to create the fuel had been captured in a power plant it could theoretically cut overall emissions, because each molecule of CO2 would be used twice. They could even be net-zero if they were produced using CO2 captured from the air (https://www.carbonbrief.org/swiss-company-hoping-capture-1-global-co2-emissions-2025).

As with shipping, the European Commission report concluded (https://www.fch.europa.eu/sites/default/files/FCH%20Docs/20200507_Hydrogen%20Powered%20Aviation%20report_FIN/ that for any of these options to scale up and compete with alternatives such as biofuels, a long-term policy framework and significant research funding will be required.

Rail

The final mode of transport that could benefit from hydrogen is rail. Hydrogen-powered trains are being rolled out slowly, with two operating (https://www.theguardian.com/environment/2018/sep/17/germany-launches-worlds-first-hydrogen-powered-train) in Germany and trials taking place in the UK (https://www.bbc.co.uk/news/av/business-54350046) and Austria (https://www.cnbc.com/2020/09/14/in-austria-a-hydrogen-train-is-set-to-travel-on-challenging-routes-.html). Plans are also underway in France and Japan.

Rail is already the most electrified mode of transport in the world, with three-quarters (https://www.iea.org/reports/the-future-of-rail) of passenger transport taking place on electric trains.

However, the IEA says that under "optimistic assumptions about fuel-cell cost reductions", unlike some other forms of transport, hydrogen may actually be competitive for rail, particularly for infrequently used lines and large, long-distance trains, such as the kind used to carry freight.

Birmingham University's prototype hydrogen fuel cell powered Hydroflex train doing test runs at Quinton Rail Tech Centre. Credit: G.P.Essex / Alamy Stock Photo.

Despite this, a recent report (https://www.networkrail.co.uk/wp-content/uploads/2020/09/Traction-Decarbonisation-Network-Strategy-Executive-Summary.pdf) by Great Britain's railway network owner Network Rail (https://www.networkrail.co.uk/) concluded that hydrogen technologies are "unsuitable for long-distance high-speed and freight services".

Specifically, the report cited (https://www.networkrail.co.uk/wp-content/uploads/2020/09/Traction-Decarbonisation-Network-Strategy-Interim-Programme-Business-Case.pdf) the need for eight times the storage volume for hydrogen fuel compared to diesel, as well as the fact that, to date, no hydrogen-powered freight or high-speed trains are available.

Instead, the report frames hydrogen primarily as a solution to low-speed passenger train lines in rural areas, or to deal with "off-wire" sections, such as tunnels and bridges, that are hard to electrify with overhead wires.

Some have suggested (https://theconversation.com/hydrogen-trains-are-coming-can-they-get-rid-of-diesel-for-good-110450) that the high cost of installing overhead wires in some locations makes hydrogen a more economic option in certain cases.

Another report (https://www.rssb.co.uk/en/research-and-technology/sustainability/Decarbonisation/Decarbonisation-our-final-report-to-the-Rail-Minister), produced last year for the UK rail minister by the Rail Industry Decarbonisation Task Force (https://www.rssb.co.uk/), notes that "the future cost of hydrogen is unpredictable, especially given the lack of certainty on means of production".

In the UK, CO2 emissions from trains have already been cut (https://www.rssb.co.uk/en/research-and-technology/sustainability/Decarbonisation/Decarbonisation-our-final-report-to-the-Rail-Minister) by 50% over the past decade as further lines have been electrified and as the electricity system has been decarbonised.

National Rail envisions electrification as the solution for at least around three quarters of the remaining unelectrified rail in the country. Hydrogen is identified as the best option for just 5%.

Its report also notes that, even in circumstances where it is technically possible to use batteries or hydrogen, electrification may still "represent the most sensible option".

Industry

Hydrogen's flexibility means it has a broad range of existing and potential applications in industry, including the production of fertilisers, steel and cement. It can be a chemical feedstock, a combustible fuel or a reactant to remove impurities.

All of this means that industry, particularly oil refining, ammonia and methanol production, currently makes up the bulk of hydrogen demand. This hydrogen is sourced almost entirely from fossil fuels.

Nevertheless, the fact that this demand already exists means some of these sectors could be relatively "low-hanging fruit (https://www.oxfordenergy.org/wpcms/wp-content/uploads/2020/03/Insight-66-Hydrogen-and-Decarbonisation-of-Gas.pdf)" for decarbonisation. To get there, the gas they use must be replaced with hydrogen from low-carbon sources.

Scaling up low-carbon hydrogen production for these existing sources of demand alone would be a significant undertaking, due to the sheer volumes required.

One industry that has been the focus of this discussion is steelmaking. According to Our World in Data (https://ourworldindata.org/emissions-by-sector), energy-related emissions from iron and steel manufacture account for around 7% of global greenhouse gas emissions.

Dr Alexander Fleischanderl (https://www.primetals.com/press-media/metals-magazine/issue-02-2020/what-if#:~:text=Alexander%20Fleischanderl%20joined%20Primetals%20Technologies,President%20of%20Iron%2D%20and%20S a technology officer at engineering firm Primetals Technologies (https://www.primetals.com/), tells Carbon Brief that steel manufacturers have been working to cut emissions by optimising their processes, but these efforts can only go so far:

> "There is a certain physical limit where you can go… [but] to reach the target to become net-carbon zero [these changes] won't be enough. You have to switch to hydrogen."

Steel production. Credit: Primetals.

While direct electrification of steelmaking using a process called “electrowinning (https://iopscience.iop.org/article/10.1088/1748-9326/abbd02/pdf)” could be an option in the future, it has so far only been demonstrated at a pilot scale.

Some steel is already recycled (https://www.recyclingtoday.com/article/the-growth-of-eaf-steelmaking/) from scrap using furnaces powered by electricity, which could potentially be (https://www.woodmac.com/news/opinion/how-green-can-steel-go--and-what-does-it-mean-for-coal-and-iron-ore/) decarbonised. However, according to Fleischanderl, most steel still needs to come from virgin iron ore if it is to be a high enough grade for use in the automotive industry, for example.

This relies on a process that has remained roughly the same for more than a century. Iron ore is smelted in blast furnaces with coke, which is both the fuel and the reducing agent to remove oxygen and leave pure metal behind, emitting CO2.

Hydrogen can be injected into these furnaces as a fuel, cutting emissions (https://www.mckinsey.com/~/media/McKinsey/Industries/Metals%20and%20Mining/Our%20Insights/Decarbonization%2 challenge-for-steel.pdf) by up to 20%. This technique, which is being tested (http://www.hazardexonthenet.net/article/175717/Thyssenkrupp-tests-hydrogen-as-coal-replacement-in-its-blast-furnaces.aspx) by German steel producer Thyssenkrupp, still ultimately relies on coal for reduction of the ore.

A newer production method called direct re (https://www.metallics.org/dri-production.html)duced iron (https://www.metallics.org/dri-production.html) (DRI) uses hydrogen gas as the reducing agent. This does not require a furnace to melt the ore and only water is emitted.

As it stands, around 7% (https://www.iea.org/reports/the-future-of-hydrogen) of steel is made using DRI, enough to make steelmaking the fourth biggest user of hydrogen. Scaling this process up would help the industry decarbonise if low-carbon hydrogen is used instead of hydrogen from fossil fuels, as Fleischanderl explains:

> “Technologically, there is not a big issue. Most of the things have been solved… the real roadblock is the availability of sufficient amounts and also the price of green hydrogen.”

According to (https://www.iea.org/reports/the-future-of-hydrogen) the IEA, replacing all steelmaking with DRI and electric furnaces would result in a 15-fold increase in hydrogen demand from the sector.

Pilot projects (https://www.voestalpine.com/group/en/media/press-releases/2019-11-11-h2future-worlds-largest-green-hydrogen-pilot-facility-successfully-commences-operation/) are underway in Europe to integrate low-carbon hydrogen into steelmaking, but the question of when “green steel” will be competitive remains open.

Swedish steel company SSAB (https://www.ssab.com/company/sustainability/sustainable-operations/hybrit-phases) is running the HYBRIT project (https://uk.reuters.com/article/us-sweden-steel-hydrogen/swedens-hybrit-starts-operations-at-pilot-plant-for-fossil-free-steel-idUKKBN25R1PI), which it says will achieve “fossil-free steel products” from 2026 and enable it to eradicate fossil fuels from all its operations by 2045.

Prof Ad van Wijk (http://profadvanwijk.com/) of Delft University of Technology (https://www.tudelft.nl/en/) says he is sceptical about how quickly the process will take off compared to other sectors:

> "People think that green hydrogen will first replace the grey hydrogen in industry, but I doubt if that is really going to happen…In the end it will, but at first it is difficult because of the price and the volume [required]."

One est (https://data.bloomberglp.com/professional/sites/24/BNEF-Hydrogen-Economy-Outlook-Key-Messages-30-Mar-2020.pdf)i (https://data.bloomberglp.com/professional/sites/24/BNEF-Hydrogen-Economy-Outlook-Key-Messages-30-Mar-2020.pdf)mate (https://data.bloomberglp.com/professional/sites/24/BNEF-Hydrogen-Economy-Outlook-Key-Messages-30-Mar-2020.pdf) from BloombergNEF (https://about.bnef.com/), shown in the chart below, suggests green hydrogen could compete with the most expensive coal-based steel by 2030, assuming a cost of around $2/kg for the hydrogen. Such estimates rely on a considerable fall in the cost of electrolysers and extensive renewable deployment.

Levelised costs, not including carbon prices, of steel made using hydrogen (purple line) and steel made using coal (black block). Source: BNEF (https://about.bnef.com/).

In a report (https://www.mckinsey.com/~/media/McKinsey/Industries/Metals%20and%20Mining/Our%20Insights/Decarbonization%2
challenge-for-steel.pdf) on the topic, consultancy McKinsey (https://www.mckinsey.com/) places the date when "pure hydrogen-based steel production" is cost-competitive at "between 2030 and 2040" in Europe, where the majority of green steel deployment is expected to be.

However, green steel is likely to still need considerable support from governments, potentially including an emissions trading scheme that supports (https://www.tandfonline.com/doi/full/10.1080/14693062.2020.1803040) the switch and quotas for green steel.

Fleischanderl also emphasises the importance of a carbon border adjustment (https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12228-Carbon-Border-Adjustment-Mechanism) mechanism in Europe to enable green steel to compete with cheap imports from China, the world's largest (https://www.worldsteel.org/media-centre/press-releases/2020/Global-crude-steel-output-increases-by-3.4--in-2019.html) steel producer.

“Otherwise you won’t manage it because it’s clear that green steel will cost more. That has to be accepted,” says Fleischanderl.

Thomas Blank of the Rocky Mountain Institute tells Carbon Brief that with many policymakers keen to protect steelmaking as a strategic industry, price is far from the only consideration.

He notes that while the most cost-effective location for green steel production is likely the dry north west of Australia, where iron ore is mined and renewable electricity could be cheap and plentiful, the EU and India will likely accept more expensive steel if it means keeping production local.

Another “hard-to-decarbonise” sector that could benefit (https://www.oxfordenergy.org/wpcms/wp-content/uploads/2020/03/Insight-66-Hydrogen-and-Decarbonisation-of-Gas.pdf) from the introduction of hydrogen is cement. CO2 from the chemical process of cement production makes up (https://ourworldindata.org/emissions-by-sector) 3% of global emissions, although this does not include emissions from energy inputs involved.

Burning hydrogen could reach the high temperatures needed to manufacture cement, avoiding fossil fuel combustion which currently accounts for a third of its emissions.

However, progress in this area is currently very limited and replacing fossil fuels would require a whole new infrastructure as existing cement kilns would not work with pure hydrogen.

A UK government feasibility study (https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/866365/Phase_2_-_MPA_-_Cement_Production_Fuel_Switching.pdf) published last year examined a mix of biomass and hydrogen to manufacture “net-zero” cement, noting that hydrogen had “never been tested” in this context. A project has since (https://www.constructionmanagermagazine.com/mpa-wins-6m-cement-carbon-reduction-research/) received £6m ($8m) in funding to test the idea.

Other industrial sectors, such as the manufacture of glass, paper and aluminium, also rely on heat sources for a variety of processes including melting, drying and driving chemical reactions.

Hydrogen could be combusted or used in a fuel cell to meet some of this heat demand, although a strong policy framework will likely be needed to compete with cheap fossil gas and make up for the need for new heating equipment and what one paper (https://www.sciencedirect.com/science/article/pii/S0306261920303603?via%3Dihub) called “moderate technology readiness levels of some emerging solutions”.

As it stands there is “virtually no dedicated hydrogen production for generating heat” and it is expected to “compete poorly” with biomass and CCS, according to (https://www.iea.org/reports/the-future-of-hydrogen) the IEA.

The agency says it could compete with electrification of industrial heat, although electricity is already far more developed. One study (https://iopscience.iop.org/article/10.1088/1748-9326/abbd02/pdf) found that 78% of European industry’s energy demand is already electrifiable using established technologies.

As for industrial processes that already rely heavily on hydrogen, while efficiency improvements may curb some of their demand, overall it is expected to grow. This means businesses will need to seek low-carbon hydrogen sources in order to decarbonise.

The single sector with the largest demand (https://www.iea.org/fuels-and-technologies/hydrogen) is oil refining, where hydrogen is used to remove sulphur and other impurities.

While oil use is likely to decline in line with climate action, tightening regulations on sulphur content in fuels mean there is still likely to be sizable demand for hydrogen in this sector.

Hydrogen is also a major feedstock for the chemical industry, particularly to make ammonia for fertilisers and methanol for solvents, adhesives and various other substances.

Demand for these substances is expected to grow in the coming decades. However, it could grow even further if these chemicals become established as either ways of transporting hydrogen over long distances, or as alternative fuels in their own right.

Despite its toxicity, ammonia in particular is being discussed as an alternative to hydrogen in some applications, particularly shipping (See: "Transport"). It can potentially (https://royalsociety.org/topics-policy/projects/low-carbon-energy-programme/green-ammonia/) be stored and transported

more easily than hydrogen as it is a liquid at relatively low pressure and either converted back into hydrogen or burned without generating CO2.

At a recent EurActiv event (https://events.euractiv.com/event/info/ammonia-the-missing-link-in-the-hydrogen-story), European Commission energy adviser Tudor Constantinescu (https://energystorageforum.com/speaker/tudor-constantinescu-2) said he saw such hydrogen-derived fuels playing "a very important role" in a fully decarbonised economy.

Low-carbon hydrogen could be critical to decarbonising all of these applications, but its success will depend on competition with gas using CCS and biomass, both of which could also be used to cut emissions from industry.

Dr Tom Brown (https://nworbmot.org/) of the Karlsruhe Institute of Technology (https://www.kit.edu/english/index.php), tells Carbon Brief that this helps to explain why there is so much variation (https://publications.jrc.ec.europa.eu/repository/bitstream/JRC118592/towards_net-zero_emissions_in_the_eu_energy_system_-_insights_from_scenarios_in_line_with_2030_and_2050_ambitions_of_the_european_green_deal_on.pdf) in projections of hydrogen use. "I don't think anyone knows quite which one will make the most headway," he says.

Whichever solutions come out on top, the IEA illustrates (https://www.iea.org/reports/the-future-of-hydrogen) the urgency of scaling them up quickly to tackle emissions from industry.

In its hydrogen report (https://www.iea.org/reports/the-future-of-hydrogen), the agency calculates that to meet future ammonia and methanol demand while limiting warming to well-below 2C using fossil gas, CCS units capturing 1MtCO2 each year would have to be built at a rate of four per month between now and 2030.

If green hydrogen is used to achieve the same goal, six or seven new 100MW electrolysers would have to be built every week until 2030.
According to the IEA, 2021 is currently set (https://www.iea.org/data-and-statistics/charts/global-electrolysis-capacity-becoming-operational-annually-2014-2023-historical-and-announced) to see closer to the equivalent of four 100MW electrolysers becoming operational across the entire year.

Electricity

Hydrogen's versatility means it could have various applications in the power sector, including replacing fossil gas in retrofitted power plants and providing electricity (https://www.bbc.com/future/article/20190327-the-tiny-islands-leading-the-way-in-hydrogen-power) on remote islands using fuel cells.

In particular, there are two valuable roles that hydrogen could play in the power system.

> **JesseJenkins**
> @JesseJenkins
>
> Blending hydrogen w/natural gas in conventional gas turbines & increasing to 100% hydrogen over time seems like a promising route to clean firm power for affordable, reliable 100% carbon-free grid. Lots of recent effort from turbine makers. Most recent: dieselgasturbine.com/ge-uniper-anno....
>
> GE, Uniper Announce Decarbonization Collaboration - Diesel & G...
> 'Roadmap' sought to increase use of hydrogen in turbines, compressors
> dieselgasturbine.com
>
> 8:40 AM · Jul 23, 2020
>
> 151 54 people are Tweeting about this

First, it has been proposed as a flexible source of potentially low-carbon electricity that can be used to complement grids dominated by variable renewables, such as wind and solar.

Second, electrolysers could be used to produce hydrogen using “curtailed (https://reneweconomy.com.au/could-hydrogen-be-the-answer-to-wind-and-solar-curtailment-woes-92174/)” electricity generation that would otherwise go to waste during particularly sunny or windy periods when renewable supply exceeds demand.

Wind farm in cloudy morning light at Madfeld, Germany. Credit: Mauritius Images GmbH / Alamy Stock Photo.

As renewables supply more of the world’s power, hydrogen advocates (https://www.scientificamerican.com/article/solar-and-wind-power-could-ignite-a-hydrogen-energy-comeback/) see the gas as an essential component for “deep decarbonisation (https://www.carbonbrief.org/reports-show-how-uk-and-the-world-can-achieve-deep-decarbonisation)”, providing electricity when the sun and wind are insufficient.

In this case, hydrogen could be a useful form of energy storage, covering seasonal variation in renewable-heavy systems when batteries are insufficient.

Renewable electricity, sourced from domestic grids at times when it is abundant and cheap, can be converted into hydrogen. Alternatively, it can be imported from nations that have a surplus of wind or sun (See: “How will hydrogen affect global geopolitics?”)

Hydrogen can be stored by compressing it into underground salt caverns or depleted fossil fuel sites, blended with fossil gas or used to produce other fuels. It can then be converted back into power when required, or used for other purposes in the energy system, such as transport fuels.

In the short term, batteries tend to provide (https://www.oxfordenergy.org/wpcms/wp-content/uploads/2020/03/Insight-66-Hydrogen-and-Decarbonisation-of-Gas.pdf) a superior storage system, with round-trip efficiency (https://energymag.net/round-trip-efficiency/#:~:text=Energy%20storage%20typically%20consumes%20electricity,)%2C%20expressed%20in%20percents%20 (ratio of energy in to energy out) of more than 80%, compared to 35-41% (https://cadmus.eui.eu/bitstream/handle/1814/66205/RSCAS_PP_%202020_01rev2.pdf?sequence=6&isAllowed=y) for hydrogen.

However, hydrogen can be used when energy needs to be stored for days or weeks as batteries suffer from self-discharge (https://gcep.stanford.edu/pdfs/HydrogenBatteries_GridStorage.pdf) over longer time periods.

It also makes more sense for larger-scale storage requirements, which would require "immense" numbers of batteries compared to the space taken up by hydrogen storage, according to (https://www.iea.org/reports/the-future-of-hydrogen) the IEA.

Despite these applications, Dr Tom Brown (https://nworbmot.org/) of the Karlsruhe Institute of Technology (https://www.kit.edu/english/index.php), who has modelled (https://www.researchgate.net/publication/340883990_Early_decarbonisation_of_the_European_energy_system_pays_off) deep decarbonisation pathways for Europe, says the power sector is unlikely to be the first priority for an extensive hydrogen rollout. He tells Carbon Brief:

> "If you were removing a tonne of CO2, it would make more sense to put the hydrogen in the steel or ammonia sectors than worrying about the last 10% of the electricity demand decarbonisation."

Brown says it is "more economical" to source as much electricity from renewables as possible before turning to electrolysis and green hydrogen.

After the production and storage infrastructure is in place to supply other sectors, such as industry, hydrogen for backup power generation could naturally follow, he says: "You sort of get the hydrogen and this last 10-20% of a 100% renewable world for free, essentially."

According to a report (https://cadmus.eui.eu/bitstream/handle/1814/66205/RSCAS_PP_%202020_01rev2.pdf?sequence=6&isAllowed=y) from the European University Institute (https://www.eui.eu/), using hydrogen for electricity storage is "largely overestimated" simply because, in Europe at least, periods without sun or wind are not actually very common:

> "There is more production of offshore wind in winter than in summer and transmission grids connect the countries in Europe quite effectively."

However, making use (https://link.springer.com/article/10.1007/s11708-018-0588-5) of curtailed power has been proposed as a strategy that makes sense not only to cut emissions, but to save money.

A report (https://nic.org.uk/app/uploads//Net-Zero-6-March-2020.pdf) on net-zero opportunities for the UK power sector by the National Infrastructure Commission (https://nic.org.uk/) (NIC) concludes that producing hydrogen fr curtailed electricity "could help to reduce system costs in highly renewable mixes".

IRENA states that (https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Sep/IRENA_Power-to-Hydrogen_Innovation_2019.pdf) this "can significantly help improve the economics of hydrogen production" and also provide revenues for renewable asset owners.

These periods are becoming more common with rising renewable penetration, as Ben Gallagher of Wood Mackenzie tells Carbon Brief:

> "[In] California, Germany, western China and west Texas, the frequency of curtailments and negative power price events (https://www.cleanenergywire.org/factsheets/why-power-prices-turn-negative) is increasing, so hydrogen via electrolysis, very similar to energy storage, is thought of as a potential tool to help manage grid flexibility."

While this is a promising idea it may not be practical, even assuming a significant rollout of renewables in the coming years. The NIC notes (https://nic.org.uk/app/uploads//Net-Zero-6-March-2020.pdf) that "it will be challenging to absorb all curtailed renewable generation at low cost due to the volatility of its production".

Solar Array at Hill Canyon Wastewater Treatment Plant in California, which provides about 15% of the facility's energy needs. Credit: Citizen of the Planet / Alamy Stock Photo.

Electrolysers built solely to make use of this otherwise wasted power may only (https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Sep/IRENA_Hydrogen_2019.pdf) operate around 10% of the time, IRENA notes. This is due to curtailment being an occasional event, when conditions are particularly sunny or windy.

Such low utilisation rates mean the hydrogen they produce may not be competitive, owing to the costs associated the electrolysers themselves.

On the other hand, as Gniewomir Flis of Agora Energiewende has pointed out, declining electrolyser costs could help hydrogen from curtailed power compete with fossil fuel hydrogen.

Gniewomir Flis
@gnievchenko

Replying to @gnievchenko

If you're getting curtailment only from one source or the other, and purchased your electrolyser at $450/kW CAPEX, can just about produce H2 at $2/kg.

Congratulations, you can now compete with fossil fuel H2, and upset the status quo for ammonia and petrochemical markets.

7:31 AM · Feb 18, 2020

This analysis is based on proton exchange membrane (https://www.fuelcellstore.com/fuel-cell-components/membranes) (PEM) electrolysers, which, unlike the more widely used alkaline electrolysers, are able to quickly ramp up and capture curtailed energy.

While China, the world's biggest electrolyser producer, has pioneered the production of relatively cheap alkaline electrolysers, PEM electrolysers are currently too expensive (https://twitter.com/gnievchenko/status/1229760362620346368) to produce cost-competitive hydrogen from curtailed power.

But as the EU ploughs ahead with its hydrogen strategy, it has committed (https://www.euractiv.com/section/energy/news/europe-china-battle-for-global-supremacy-on-electrolyser-manufacturing/) to investing in the production of "innovative technologies", such as PEM, in a bid to keep its economy competitive and bring prices down.

Heat for buildings

Space heating and hot water supply for buildings is one of the most contested areas of potential hydrogen use and is often the subject of heated (https://www.installeronline.co.uk/government-demonizing-gas/) debate.

Many energy (https://www.iee.fraunhofer.de/en/presse-infothek/press-media/overview/2020/Hydrogen-and-Heat-in-Buildings.html) experts (https://about.bnef.com/blog/liebreich-separating-hype-from-hydrogen-part-two-the-demand-side/) are (http://www.csrf.ac.uk/2020/09/hydrogen-for-heating/) dismissive (https://cadmus.eui.eu/bitstream/handle/1814/66205/RSCAS_PP_%202020_01rev2.pdf?sequence=6&isAllowed=y) of the idea of hydrogen playing a large role in decarbonising building heat, because it is far less efficient than electric heat pumps, making it more costly to run.

Others argue it can tackle (https://www.energynetworks.org/creating-tomorrows-networks/gas-goes-green) the problem of decarbonising heat without disrupting (https://www.northerngasnetworks.co.uk/wp-content/uploads/2017/04/H21-Report-Interactive-PDF-July-2016.compressed.pdf) peoples' lives (https://www.h21.green/wp-content/uploads/2018/01/SBT2251-Leeds-Beckett-Leeds-Sustainability-Institute-H21-Report-Singles.pdf), at lower upfront cost and while reusing valuable gas distribution assets. They also point to constraints on the electricity grid, which might need upgrading to cope with fully electrified heat.

Overall, efficiency and electrification are the primary routes to decarbonising heat, says Jenny Hill (https://www.theccc.org.uk/author/jenny-hill/), head of buildings and international action at the UK's advisory Climate Change Committee (https://www.theccc.org.uk/), but hydrogen could play an important secondary role. She tells Carbon Brief:

> "Efficiency is the essential first step or the heat problem gets too big. While electrification is of primary strategic importance, hydrogen can play an incredibly useful role in meeting peaks – in the power sector, or through use of hybrid heat pumps [see below] – as well as a role regionally."

Heat for buildings is a major problem to address. According to the IEA (https://www.iea.org/reports/the-future-of-hydrogen), heat use in buildings accounts for more than 20% of global final energy demand, including space heating, hot water and cooking.

This 20% share can be compared with hydrogen uptake in the deep decarbonisation scenarios shown above (See: How much hydrogen is needed to limit climate change?), where a maximum 24% of final energy in 2050 is supplied by hydrogen, for all uses.

Moreover, most hydrogen in these studies is used for industry, transport or power, rather than buildings. This suggests it would not be cost optimal to use hydrogen to decarbonise most of the world's building heat demand. Nevertheless, it may be needed where alternatives are not viable.

Some countries (https://twitter.com/janrosenow/status/1326145348738408448) have already made rapid strides towards decarbonising the provision of heat, using electricity or district heating. But, in many others, there has been limited (https://ec.europa.eu/eurostat/statistics-explained/index.php?title=File:Share_of_energy_from_renewable_sources_for_heating_and_cooling,_2004-2018_(%25).png) progress.

Tackling heat emissions is generally recognised as challenging, particularly for less well insulated existing buildings, which the IEA says will still make up two-fifths of the global stock by 2050.

Globally, some 41% of building heat currently comes from burning gas, the IEA says, with wide variation from country to country. This is shown in the chart, below, with gas (dark grey) supplying around 80% of heat in the Netherlands and the UK, but closer to zero in Nordic countries.

Share of building heat supplied by gas (dark grey), electricity (blue), district heat (orange) and other fuels, %, in a range of countries. Source: Vivid Economics 2017 (https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/699674/050218_International_Comparisons_Study_MainReport_CLEAN.pd report for the UK government, as cited in Chatham House 2019 (https://chathamhouse.soutron.net/Portal/DownloadImageFile.ashx?objectId=3077).

The widespread use of gas-fired heating is an opportunity for hydrogen, advocates say, because it can act as a "like-for-like (https://mediacdn.baxiheating.co.uk/-/media/websites/baxiuk/images/news-images/hydrogen-taskforce-report-feb2020_web.pdf?la=en&v=1&d=20200311T163010Z&hash=DE008ECD19A06A730C2ADD84242D2732)" replacement for the fuel. Hydrogen can be burned in a modified gas boiler (https://www.worcester-bosch.co.uk/professional/news/uks-first-hydrogen-heating-demonstration-takes-place) or hob, with fuel supplied by a repurposed network (https://www.businessgreen.com/news/4018567/pipe-upgrade-project-set-slash-methane-footprint-britain-gas-network) of gas distribution pipes.

Coalitions (https://www.hy4heat.info/) of companies (https://www.h21.green/) in the UK have been working to test the idea for several years, with the aim (https://www.h21.green/news/north-sea-ammonia-shipping-2/) of converting "significant parts of the UK gas grid to be 100% hydrogen". The government's recent climate plan (https://www.carbonbrief.org/media-reaction-boris-johnsons-10-point-net-zero-plan-for-climate-change) aims to test hydrogen heat in a whole town by 2030.

Internationally, there are at least 37 projects (https://webstore.iea.org/download/direct/2803) testing the blending of hydrogen into existing gas grids, thought to be safe up to 20% by volume without changes for consumers. This is seen as a "low-regrets" way to reduce CO2 from heating and scale up hydrogen use.

The UK's network of gas transmission pipes – historically made from leaky and corrosion-prone iron – is already being replaced with "hydrogen-ready" plastic pipes, though compressors and other parts of the network would also need replacement to cope with 100% hydrogen use.

The iron mains replacement will be complete by 2032, says Matthew Hindle (https://www.linkedin.com/in/matthew-hindle-94453122?originalSubdomain=uk), head of gas at the Energy Networks Association (https://www.energynetworks.org/), which represents gas and power distribution companies in the UK.

Carl Arntzen, chief executive of boiler manufacturer Worcester Bosch (https://www.worcester-bosch.co.uk/professional/), tells Carbon Brief that, in his view, hydrogen is the best solution for all of the 85% of UK homes currently heated with fossil gas.

He points to practical challenges for heat pumps, including the need to upgrade building energy efficiency, replace radiators and find space for hot water tanks and heat pump equipment.

Carl Arntzen, Worcester Bosch CEO and Rishi Sunak, the Chancellor, with a hydrogen-ready boiler. Credit: Worcester Bosch.

The idea of disruptive change to homes and behaviours is often "front of mind" for people thinking (https://www.h21.green/wp-content/uploads/2018/01/SBT2251-Leeds-Beckett-Leeds-Sustainability-Institute-H21-Report-Singles.pdf) about the future of heat (https://medium.com/@guynewey/five-steps-to-net-zero-levels-of-innovation-fa12ee0a3bbf), says the ENA's Hindle. (Recently, the UK climate assembly (https://www.carbonbrief.org/qa-how-the-climate-assembly-says-the-uk-should-reach-net-zero) found strong support for hydrogen, heat pumps and heat networks to tackle heat decarbonisation.)

But while major efficiency upgrades may be disruptive, they are likely to be needed in any case. Dr Richard Lowes (https://geography.exeter.ac.uk/staff/index.php?web_id=Richard_Lowes) at the University of Exeter (https://www.exeter.ac.uk/), tells Carbon Brief: "In every bit of analysis I've seen, whether it's hydrogen or electrification, you have to do efficiency to make things cost effective."

On costs, recent analysis (https://pubs.rsc.org/en/content/articlelanding/2020/ee/d0ee02016h#!divAbstract) shows hydrogen for heat would be around three times more expensive than gas, whereas heat pumps are as cheap to run (https://ukerc.ac.uk/publications/net-zero-heating/) as gas boilers in some circumstances.

BNEF's Meredith Annex says using hydrogen for heat is an "expensive use case" and that the fuel "struggles" relative to heat pumps, even on a total cost-of-ownership basis.

Another frequently cited issue for the widespread use of heat pumps is that it would significantly increase peak demand on the electricity grid, particularly in high-latitude countries, such as the UK.

This point is often accompanied (https://www.carbonbrief.org/ccc-uk-must-act-now-secure-zero-carbon-heat-2050) by versions of the chart, below, showing seasonal variations in half-hourly UK energy demand currently met by electricity (blue line) versus gas for heat (red). (Carbon Brief understands a similar chart is on the business card of some within the gas industry.)

Half-hourly demand for heat and electricity in the UK, gigawatts. Heat demand is an estimate. Source: Managing Heat System Decarbonisation (https://www.imperial.ac.uk/media/imperial-college/research-centres-and-groups/icept/Heat-infrastructure-paper.pdf), Imperial College Centre for Energy Policy and Technology.

This chart suggests meeting peak heat demand with electricity could require a massive increase in the size of the power system, with peak electricity demand rising as much as five- or six-fold.

But more recent evidence (https://www.sciencedirect.com/science/article/pii/S0301421518307249?via%3Dihub) shows that demand for heat energy is some 40-50% lower than thought, at closer to 170 gigawatts (GW) rather than the peak of 300GW shown in the chart above. This would be reduced further (https://twitter.com/dustin_benton/status/1125737793811095552) with the energy efficiency improvements required on the road to net-zero.

Moreover, heat pumps work by drawing warmth from outside air, multiplying the energy used to run them by two or three times, depending on device performance and ambient temperatures. This could cut the highest peaks (https://blogs.exeter.ac.uk/energy/2017/07/10/is-the-peak-heat-issue-all-its-made-out-to-be/) in heat energy demand in half again.

Even so, the remaining additional peak demand for electric heat during cold winter evenings could strain the electricity grid. Although it would be possible to cover these peaks, it could be expensive.

This is where hydrogen could step in, according to analysts including the CCC and BNEF. They point to the use of "hybrid" heat systems that mostly run on electricity, but use hydrogen boilers to "top up" on the coldest days, much as gas with carbon capture and storage or hydrogen-fired peaking electricity plants could be used to fill gaps in output from wind and solar power.

Another option would be for certain areas to be heated with hydrogen, particularly around regional "hubs" where use of the fuel – and associated infrastructure – is widespread.

In research (https://www.sciencedirect.com/science/article/pii/S2210422420300964) published in August, Lowes and colleagues argue that heating industry "Incumbents are over-selling 'green-gas' to policymakers in order to protect their interests and detract from the importance and value of electrification." Their paper says:

> "Techno-economic analysis by academia, the UK government and its advisors has repeatedly suggested that electrification of much heat demand, primarily using heat pumps alongside the reduction in heat demand, represents the lowest cost pathway to near fully decarbonised heating."

A review (https://ukerc.ac.uk/publications/net-zero-heating/) of the options from the UK Energy Research Centre (https://ukerc.ac.uk/) (UKERC) concludes that "electrification and energy efficiency remain the two main strategies for decarbonising the building sector". It says hydrogen could play a role if "significant uncertainties" are resolved.

While Lowes and others support large hydrogen trials to evaluate the potential of the fuel, they warn that this work should not be used as an excuse to avoid making progress with other options.

In a recent blog, Stian Westlake (https://www.nesta.org.uk/team/stian-westlake/), executive director at UK innovation foundation Nesta (https://www.nesta.org.uk/), discussed the broader, related problem of "bionic duckweed", where the promise of new technological solutions in the future is used to hold back the use of existing options. He wrote (https://medium.com/@stianstian/bionic-duckweed-using-the-future-to-fight-the-present-3e471b642c28):

> "While I don't doubt there are some good-faith enthusiasts for hydrogen home heating, I wonder if a lot of the enthusiasm is about deploying a warm fuzz of futurism to block the present-day threat of heat pumps."

Dr Jan Rosenow from the Regulatory Assistance Project (https://www.raponline.org/) tells Carbon Brief:

> "I think a reasonable approach would be stepwise, where you test hydrogen use and then roll out the infrastructure more gradually, rather than having a grand plan that it's all going to be about hydrogen…To me, that seems misguided. And it's a deeply dangerous strategy that could completely fail – and then in 10 years time you haven't done anything."