



[4] Whyhydrogen? Use cases may be narrower than advertised, and the timeline is a long one

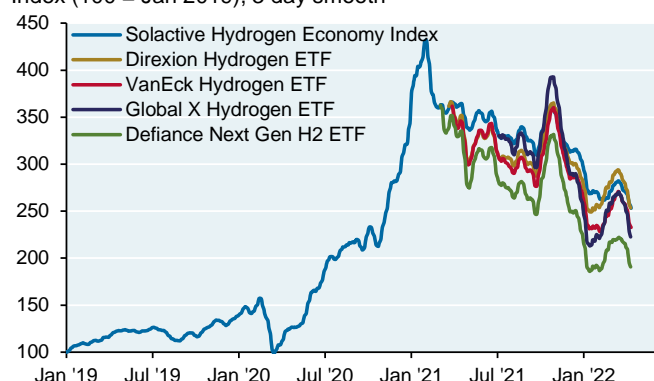
There's a lot of excitement about hydrogen. As shown below, hydrogen-linked equities quadrupled from 2019 to 2021 before falling 35%-40% from peak levels. Enormous hydrogen research reports are commonplace now, extolling the long-awaited arrival of the hydrogen economy²⁵. Hydrogen is also mentioned as a critical option for Europe to reduce reliance on imported Russian energy.

To be clear, the hydrogen economy is in its infancy other than legacy hydrogen uses completely reliant on fossil fuels. As shown in the second chart, 90 million metric tons of hydrogen are used each year to produce ammonia for fertilizer, and in oil refining to reduce the sulfur content of diesel fuel. A very small amount is also used in steel production as an iron ore reducing agent alongside carbon monoxide. **In other words, almost no hydrogen is used in power, transport, home heating, shipping, rail, aviation or other widely discussed use cases.** And: practically all hydrogen is created via steam reformation of fossil fuels (grey hydrogen), with less than 1% created via electrolysis using renewable energy (green hydrogen). Hydrogen is not a native energy source, it's an energy carrier: ~2% of global primary energy is converted into hydrogen each year, a level roughly unchanged since the year 2000.

I got into a discussion with some bullish hydrogen energy analysts recently and it led to a longer conversation about hydrogen use cases. This section is a synopsis of that discussion.

The performance of hydrogen linked equities

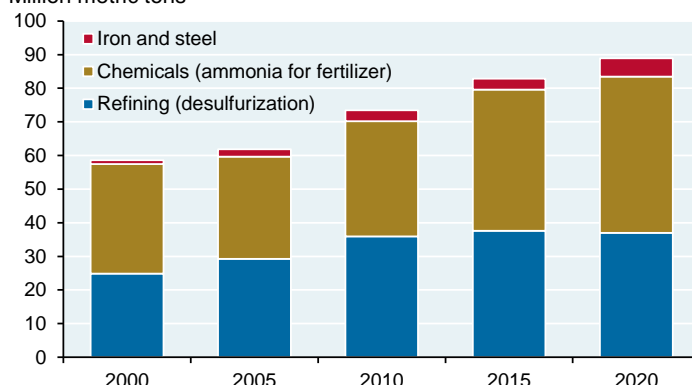
Index (100 = Jan 2019), 3 day smooth



Source: Bloomberg. May 3, 2022.

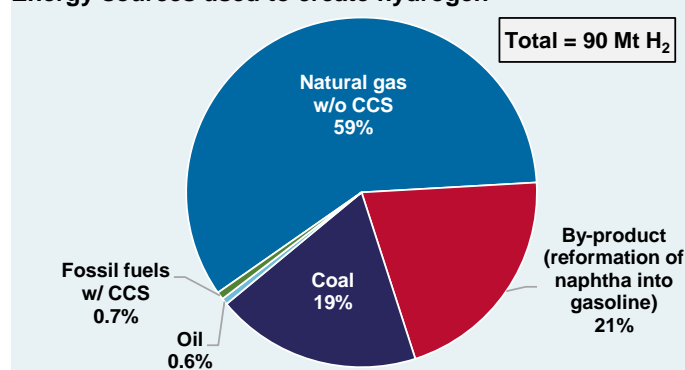
Hydrogen demand by sector

Million metric tons



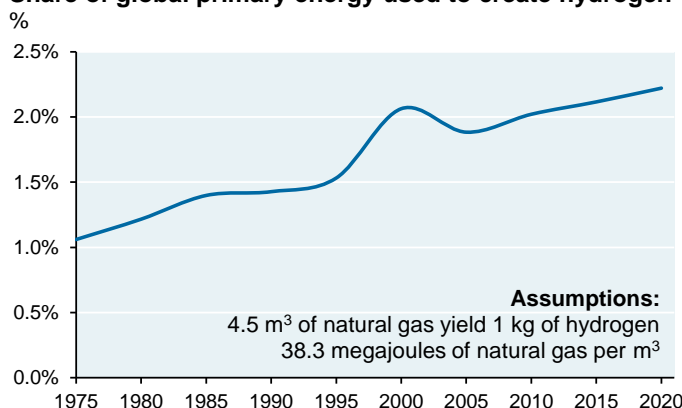
Source: IEA. 2021.

Energy sources used to create hydrogen



Source: IEA. 2020. CCS = Carbon capture and storage.

Share of global primary energy used to create hydrogen



Source: IEA, S&P Global, BP, NREL, JPMAM. 2020.

²⁵ Examples include these behemoths: “Global Hydrogen Review”, International Energy Agency, 2021, 223 pages; “Carbonomics: The clean hydrogen revolution”, Goldman Sachs, February 2022, 144 pages; “Hydrogen: A climate megatrend”, Barclays, May 2020, 66 pages; “EMEA Hydrogen: A revolution in need of realism”, JP Morgan, February 2021, 157 pages; “Green Hydrogen Cost Reduction”, IRENA, 2020, 106 pages



The long and winding road: a discussion with hydrogen optimists (HO) on the future

Natural gas field compressors and grey hydrogen energy math

- **HO:** In the US, 25,000 upstream, midstream and downstream natural gas field compressors account for 2%-3% of US natural gas consumption²⁶. Midstream energy companies are now considering hydrogen to power them instead. GE has designed hydrogen fueled compression turbines with more than 100 in operation
- **MC:** Yes, but if they use today's "grey" hydrogen produced via steam methane reformation of fossil fuels (SMR) to power these compressors, they would *increase* CO₂ emissions compared to using natural gas directly due to the ~30% losses involved in the conversion of natural gas to hydrogen²⁷

Pipeline blending

- **HO:** What about midstream companies considering hydrogen blends in existing natural gas pipelines?
- **MC:** Again, that only makes sense when using "green" hydrogen produced via renewables. In other words, it would make no sense to blend grey hydrogen into natural gas pipelines given the increase in CO₂ emissions that would entail (applying the same logic with respect to pipeline compressors). There's also the question of whether natural gas pipelines can physically *withstand* a lot of hydrogen
- **HO:** What do you mean; there are already hydrogen blending pilot projects underway
- **MC:** Pipeline engineers have to look for "embrittlement" which refers to cracking and other pipeline degradation. Valves, flanges, compressors and tubes need to be retested and at hydrogen blend rates over 10% some equipment might have to be replaced. While pilot programs have been launched in Scotland, Australia, Colorado, California and Long Island, pipeline blending needs more research. A new NREL study found that physical properties of steel, polyethylene and rubber are changed by exposure to hydrogen; and that hydrogen permeates metal and can permeate polyethylene walls 5x faster than methane²⁸. Hydrogen leakage is also affected by pressure, contaminants, the angle of the pipeline and other factors
- **MC (continued):** Even without leakage, hydrogen blending in gas pipelines has plenty of skeptics. The Fraunhofer Institute found that hydrogen blending would reduce emissions by 6%-7% and increase energy costs by 43%; the IEA estimates that hydrogen blending equates to emissions abatement costs of \$500 per tonne of CO₂; and Agora Energiewende estimates that adding 20% hydrogen to the gas grid would increase European consumer heating costs by 33% in 2030

Blue hydrogen and commercial demand for CO₂

- **HO:** What if these field compressors and pipeline blends used "blue" hydrogen instead, which refers to grey hydrogen production combined with geologic sequestration of CO₂ via carbon capture and storage (CCS)?
- **MC:** CCS is the most overhyped industrial process in the modern era, with hundreds of academic papers written and still just 0.1% of global CO₂ emissions are sequestered underground. Europe is forging ahead with 76 CCS projects, mostly dedicated to enhanced oil recovery (EOR)²⁹. Even so, Europe's sequestration potential from these projects in 2030 is 50 million metric tons per year of CO₂, which is 1% of its annual emissions. US sequestration potential from projects under development also amount to less than 2% of US CO₂ emissions³⁰. Similarly, McKinsey estimated that global sequestration may only reach 1% of global emissions in 2030, and that's with supportive policies in place³¹. The CCS infrastructure required for a more substantial impact would be enormous, and rival the size of existing oil pipeline infrastructure³². By the way, recent research has thrown cold water on the climate benefits of blue hydrogen production

²⁶ "US Natural Gas Compression Infrastructure: Opportunities for Efficiency Improvements", Ebara Corp, 2018

²⁷ "Updates of Hydrogen Production from SMR Process", Argonne National Labs, 2019

²⁸ "Hydrogen blending into natural gas pipeline infrastructure", Topolski et al, NREL, October 2022

²⁹ "CCUS In Europe", IFRI Center for Energy & Climate, August 25, 2021 and Global CCS Institute

³⁰ "Global Status of CCS 2021", Global CCS Institute, October 2021

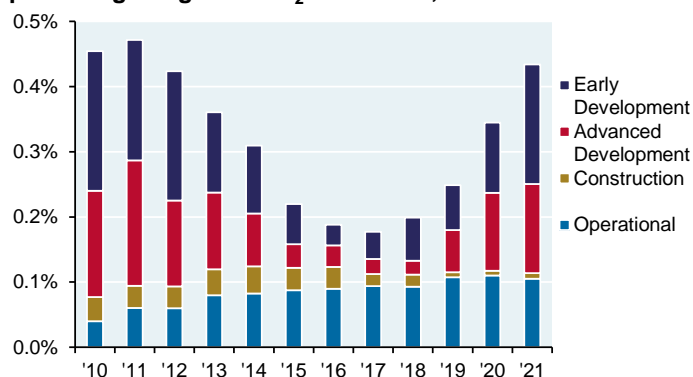
³¹ "Driving CO₂ emissions to zero (and beyond) with carbon capture, use and storage", McKinsey, June 2020

³² See "Future shock", annual energy Eye on the Market, 2021, page 22



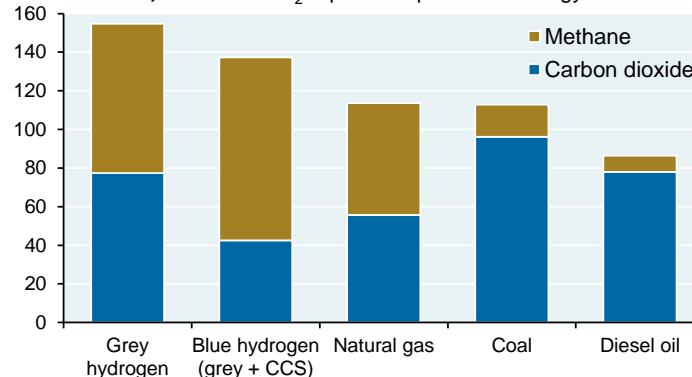
- **HO:** What cold water is that?
- **MC:** Robert Howarth at Cornell estimates that the GHG impact of blue hydrogen is more than 20% higher than the GHG impact of just burning natural gas or coal directly³³, due to additional energy demands of CCS, a typical capture rate that's well below 100% and the energy intensity of grey hydrogen production
- **HO:** Even so...what if there were growth in commercial demand for the CO₂ that grey hydrogen produces? CO₂ could be used for enhanced oil recovery (EOR) and other commercial applications
- **MC:** I don't get the sense that there's that much commercial demand for CO₂. It's only used in 2.5% of US crude oil production, and global EOR consumption of CO₂ in 2019 was just 72 million metric tons, which is 0.2% of global emissions. McKinsey cites potential CO₂ demand of 10,700 million metric tons in 2030 from producers of synthetic and algae based fuels³⁴, but that's another one of those "anything could happen" renewable energy forecasts which have little basis in currently commercialized fuel systems
- **HO:** Existing CCS distribution networks are small, but what if large portions of the US natural gas pipeline network were repurposed for carbon instead once enough wind and solar exist?
- **MC:** I cannot envision such a thing taking place in my lifetime, and I am 60

Global carbon capture and storage capacity as a percentage of global CO₂ emissions, %



Source: Global CCS Institute. 2021.

Blue hydrogen GHG higher than direct natural gas combustion, Grams of CO₂ equivalent per MJ of energy



Source: "How green is blue hydrogen?" Howarth (Cornell). July 2021.

³³ "How green is blue hydrogen?", Robert Howarth et al, Energy Science Engineering, 2021

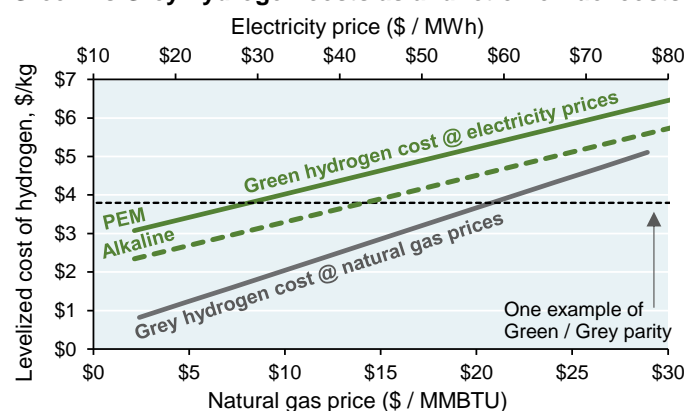
³⁴ "Driving CO₂ emissions to zero (and beyond) with carbon capture, use and storage", McKinsey, June 2020



Green hydrogen costs

- **HO:** OK, so let's talk about green hydrogen costs. Goldman Sachs projects steep declines in electrolysis costs that are similar to those achieved during prior learning curves on wind, solar and batteries (see page 39)
- **MC:** Yes, they expect green hydrogen costs to decline to \$2 per kg by the end of the decade assuming high electrolyzer utilization rates, low renewable electricity costs and further declines in electrolyzer costs. That compares to current prices of \$1 - \$2 per kg for grey hydrogen, assuming natural gas prices of \$2.5 - \$10 per MMBtu (i.e., US levels). We'll see; actual adoption rates will tell us more than projections
- **HO:** In Europe, don't much higher gas prices put them a lot closer to green/grey hydrogen parity?
- **MC:** **Only if you believe that industrial companies base 20-year investment decisions on wildly gyrating spot market prices (which they generally don't).** Start with the hydrogen cost curves below. They include amortized capital costs, operating costs and fuel costs (natural gas for grey hydrogen and electricity for green hydrogen). One example of parity: unhedged grey hydrogen producers paying \$20+ per MMBtu for natural gas vs green hydrogen producers using PEM³⁵ electrolyzers paying \$30 per MWh for wind and solar power (European PPAs are \$5-\$10 higher than that right now³⁶ and may rise further given inflation across wind and solar supply chains). **But this approach is only relevant if industrial companies consider today's price levels representative of the next 10-20 years.** Obviously, in Europe a lot depends on what happens to natural gas prices as Russian pipeline gas is gradually replaced by more imported LNG. For what it's worth, the forward curve for natural gas in Europe on May 3rd priced in a 33% decline by April 2024
- **MC (continued):** I saw a chart in a hydrogen report entitled "Green H₂ Now Competitive Across Several End Uses". It showed \$5.0-\$6.5 per kg breakeven prices for green hydrogen for trucking, steel and ammonia. In my view, it was **very misleading**: the chart was based on wartime March 2022 spot prices of \$35 per MMBTU in Europe for natural gas (the spot market in Europe is already down to \$16); assumed no increase in electricity costs despite rising PPA levels; did not incorporate capital costs for steel production; and didn't make clear that the chart was only relevant for European producers. Furthermore, none of this information accompanied the chart. All of this is unfortunately standard practice in a lot of hydrogen research
- **MC (continued):** My sense is that some green hydrogen projects underway are taking place *despite* their higher costs and not because they have reached cost parity. Timeline for adoption: very long

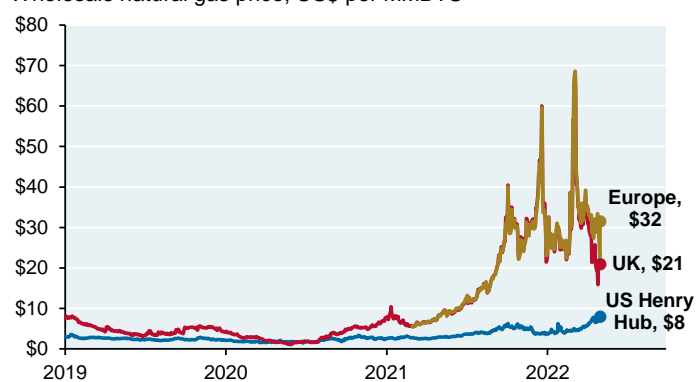
Green vs Grey hydrogen costs as a function of fuel costs



Source: Goldman Sachs Carbonomics data, JPMAM. 2022.

The US-Europe natural gas gap

Wholesale natural gas price, US\$ per MMBTU



Source: Bloomberg. May 3, 2022.

³⁵ PEM electrolyzers are considered better suited for hydrogen production relying on intermittent renewable energy, while lower-density alkaline electrolyers are targeted to bulk centralised industrial applications

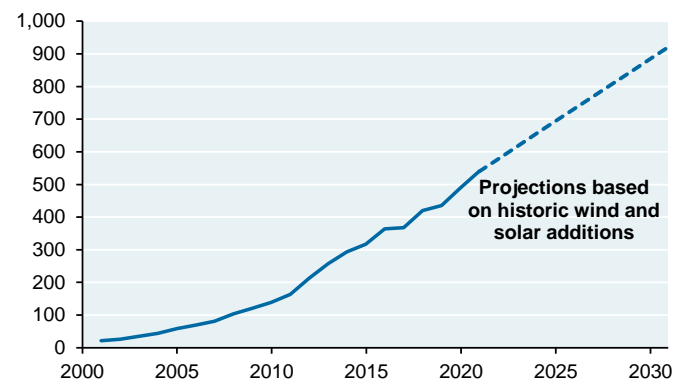
³⁶ Source: Level Ten Energy Q4 2021 PPA P25 Index. **Breakeven dynamics will be more challenging for hydrogen producers paying industrial rather than wholesale prices for electricity.** For example, US wholesale electricity prices averaged 5.6 cents per kWh in 2021 while industrial prices averaged 7.3 cents per kWh.



- **HO:** Even so, Europe looks like it will be a global leader in green hydrogen production
- **MC:** Europe plans on producing and importing green hydrogen. Let's look at European production: there's 1.5 GW of electrolyzer capacity under construction. If we add in all projects that have reached the Final Investment Decision stage as well, Europe would have 40 GW of electrolyzer capacity. If all 6 million metric tons of green hydrogen from this 40 GW³⁷ were used for oil refining, that would offset ~2.5% of EU emissions. But if the green hydrogen were used for transport instead, the emissions offset would be lower due to fuel cell energy conversion losses in vehicles. Either way, these green hydrogen projects get the process started but are not transformational. The other question: where will all the green electricity come from to *run* these electrolyzers??
- **MC:** Rystad Energy estimates that globally, announced hydrogen projects may reach 40 million metric tons per year by 2030. However, if used to replace brown hydrogen in oil refining, it would offset just 2% of global emissions, and that's assuming a zero carbon footprint for blue hydrogen projects which comprise around half of the projects Rystad analyzed. As discussed earlier, the true carbon footprint of blue hydrogen is very much still an open question.
- **HO:** What do you mean; Europe is building a lot of wind and solar power
- **MC:** **Yes, but how many energy uses can draw on the same green GW?** Europe generates ~40% of its electricity from renewables, almost half of which is from hydropower. One of Europe's primary stated goals is to further decarbonize its electricity grid. European solar and wind generation has grown at ~38 TWh per year since 2010. At the current pace, Europe will add another 380 TWh of renewable power by 2030³⁸ which would increase its renewable share of electricity generation by another 10%-15%. So if Europe's wind and solar additions are mostly used to displace coal, gas and decommissioned nuclear power on the grid, I don't see where all the new hydrogen-dedicated wind and solar capacity is going to come from. If new renewable generation is used primarily for hydrogen, then what happens to grid decarbonization?

European Union wind and solar electricity generation

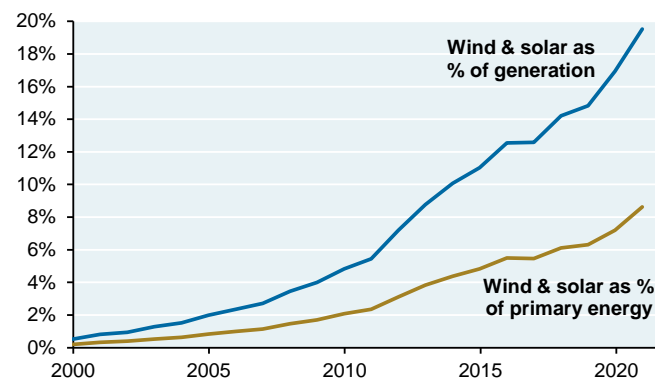
Terawatt hours



Source: Ember, Agora Energiewende. 2021.

European Union wind and solar energy

Percent



Source: BP Statistical Review of World Energy, JPMAM. 2021.

- **HO:** Don't forget about the green hydrogen that Europe plans to import as well
- **MC:** Germany just entered into a partnership with companies in the UAE to provide green hydrogen, possibly shipped in liquid form via Liquid Organic Hydrogen Carriers (see p. 34) since there are no hydrogen pipelines in place. But there are a lot of details to work out. First, this all starts with a UAE demonstration project which will generate blue hydrogen rather than green hydrogen. Other projects are underway for the importation of blue and green ammonia into Germany, but again, this is all very early stage

³⁷ Some industry sources estimate that each GW of electrolyzer capacity could produce 0.15 to 0.18 million metric tons of hydrogen per year. This implies a high efficiency rate of 80%; in practice, the efficiency rate of a 1 GW electrolyzer could be closer to 50%.

³⁸ "EU Power Section in 2020", Ember Climate research

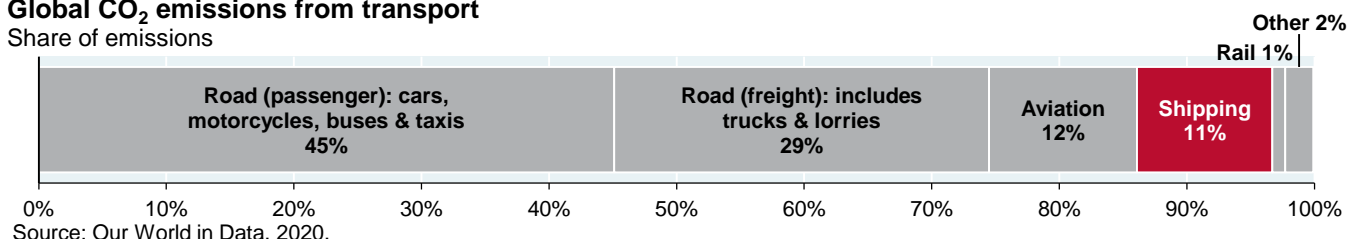


Long haul shipping using hydrogen or ammonia as fuel

- **HO:** Shifting gears for a minute, there's definitely potential for hydrogen as a fuel for long haul shipping
- **MC:** One thing's for sure: lithium ion batteries are nonsensical for shipping given cost and energy density constraints. Using state of the art electric batteries with 300 Wh/kg of energy density, an electric version of Maersk's Triple-E class containership might require 40% of its cargo capacity for batteries³⁹. There's a start-up called Fleetzero looking to electrify long-haul shipping, but they don't have a working model yet. In principle, battery cargo space could fall to 15%-20% for regional trips of 10,000 km, assuming an energy density of 470 Wh/kg, and there are plenty of studies now hailing the arrival of electrified long haul shipping that's competitive with today's ICE fleet. But some commercialization is needed for proof of concept
- **HO:** Exactly, and that's why we think green hydrogen is a better fuel for ships than batteries
- **MC:** While hydrogen has high energy density by *weight*, it has a very low energy density by *volume*. The size of hydrogen storage tanks on ships might need to be very large, and if ships used liquefied hydrogen instead the refrigeration costs could be prohibitively high (liquid hydrogen has to be stored at cryogenic conditions of -253°C). A consortium of shipping companies recently highlighted critical development issues that still to be resolved: safety considerations for cryogenic liquid hydrogen, leakage/detonation risks and the need for new bunkering infrastructure⁴⁰. A 2021 analysis in *Energy Environmental Sciences* highlights the challenge: there is no hydrogen storage solution that combines high energy density, low energy input, easily available and is easy to handle and store⁴¹
- **HO:** The challenges with using hydrogen as a shipping fuel have led some companies to focus on using ammonia as a shipping fuel instead, produced from green hydrogen via the traditional Haber-Bosch process. Wartsila and MAN have announced green ammonia engines for 2024, and large containerships designed to run on ammonia are now in the concept stage in China, Korea, Japan and the US
- **MC:** Green ammonia may be a promising hydrogen carrier given its hydrogen content (17.6%), its existing distribution network⁴², its ability to be liquefied at higher temperatures (-33°C) than hydrogen, its higher volumetric energy density vs other alternatives and relatively low energy losses when transported over long distances. The hydrogen in ammonia could then be released through catalytic decomposition, or the ammonia could be consumed directly in a fuel cell designed for it. However, all these conversions carry energy penalties: when used in transport, the round-trip efficiency of liquid ammonia produced from green hydrogen may be just 11%-19%⁴³, even lower than ICE engines at ~25%. Timeline for adoption: long

Global CO₂ emissions from transport

Share of emissions



³⁹ "Electric container ships are a hard sail", Vaclav Smil, IEEE Spectrum March 2019:22

⁴⁰ "Five lessons to learn on hydrogen as ship fuel", DNV Maritime, September 2021

⁴¹ *Challenges in the use of hydrogen for maritime applications*, Van Hoecke (Antwerp) et al, Energy Environmental Sciences, 2021. Hydrogen shipping fuel storage methods analyzed in this paper include compressed hydrogen, liquid hydrogen, ammonia, Fischer-Tropsch diesels, synthetic natural gas, methanol, formic acid, aromatic liquid organic hydrogen carriers and several solid-state hydrogen carriers

⁴² Synthetic ammonia has been used for over 100 years as fertilizer to feed 50% of the world population. Current annual production is 180 million metric tons (market value ~\$70 bn) and is distributed by barge, rail cars and pipelines as part of a worldwide market with 120 ammonia-equipped ports

⁴³ "H₂ and NH₃ – the Perfect Marriage in a Carbon-free Society", El Kadi et al (Univ. of Cambridge), May 2020



- **HO:** Well, despite these low efficiency rates, there are some large green ammonia projects underway which are targeting the shipping fuels market and land-based markets too
- **MC:** Yes, I see that. A new carbon-free city is being built in Saudi Arabia, powered by 1.2 million metric tons per year of ammonia created from solar and wind (projected completion 2025)⁴⁴. Also, Yara is planning a large ammonia project based on Netherlands offshore wind, one in Norway drawing on hydropower and another in Western Australia based on solar power. We'll see if this catches on, and at what cost after factoring in green ammonia production costs and other technical hurdles. Some estimates for green ammonia costs are 3x higher than conventional ammonia, such that green ammonia only becomes competitive at renewable power input costs of 2 cents per kWh and a carbon credit of \$100 per ton⁴⁵
- **HO:** What technical hurdles are you talking about?
- **MC:** Aligning ammonia production with renewable energy may require redesign of the energy intensive Haber-Bosch process to handle intermittent renewable energy, unless large battery storage is also deployed to store surplus renewable or thermal energy. Another issue: using a hydrogen fuel cell to harness energy stored in ammonia is complicated, since unreacted trace amounts of ammonia need to be removed to avoid poisoning fuel cell catalysts⁴⁶. Bottom line: cost, energy loss and safety issues still to be sorted out
- **HO:** What about "liquid organic hydrogen carriers" such as dibenzyl toluene? It looks like a good hydrogen storage and transportation solution since it can react with hydrogen, remain as a stable liquid within a wide range of ambient temperatures and experiences no hydrogen losses in transport
- **MC:** Primary challenges: the energy required for hydrogenation and dehydrogenation (i.e., storing and releasing the hydrogen); its hydrogen density is low at 6.2% hydrogen by weight (the mass and volume of hydrogen transport would be inefficient); and there's also a need to return the "carrier" molecules back to the point of production to transport hydrogen again. Let's see what the ultimate cost and efficiency will be

Steel production

- **HO:** What about using hydrogen as a reducing agent in primary steel production instead of carbon? Swedish steel makers and Arcelor Mittal have both announced demonstration plants to do this
- **MC:** There are pilot projects in Sweden, the UAE and elsewhere. Using green hydrogen as a reducing agent, iron ore can be transformed into sponge iron and then converted to steel in an electric arc furnace using a lot of electricity and only a small amount of carbon, possibly pulverized coal (a process referred to as H₂ DRI-EAF, Direct Reduced Iron/Electric Arc Furnace)⁴⁷. Some estimates show decarbonization potential of 70%⁴⁸
- **MC (continued):** But look at the timeline: McKinsey estimates "cash competitiveness" of Nordic hydrogen-based steel production sometime between 2030 and 2040, and that's assuming existing plants are simply written off before their useful lives are exhausted⁴⁹. The Nordics also represent just 0.5% of global production; the **elephant in the room is China which produces more than 50% of the world's steel, and whose steel plants are younger than European counterparts (i.e., much further from their "mothball" dates)**. Arcelor Mittal announced that it has now made steel in Canada via partial use of the H₂ DRI-EAF process. But only 7% of the natural gas normally used in the DRI process was replaced, and it's still a demonstration project⁵⁰. Timeline for adoption: long term, negligible global impact without China

⁴⁴ "Is ammonia the fuel of the future?", Petrochemicals Magazine, March 8, 2021

⁴⁵ "Large investments, high renewable power costs challenge green ammonia", IHS Markit, August 13, 2021

⁴⁶ "H₂ and NH₃ – the Perfect Marriage in a Carbon-free Society", El Kadi et al (Univ. of Cambridge), May 2020

⁴⁷ "Hydrogen in steel production: what is happening in Europe", Bellona Climate Foundation (Oslo), May 2021

⁴⁸ "The Potential of Hydrogen for Decarbonization: Reducing Emissions in Iron and Steel Production", Resources for the Future, Jay Bartlett and Alan Krupnick, February 2021. Hydrogen as a reducing agent might also be used for **aluminum and magnesium** but their carbon footprints are just 20% and 1% of steel, respectively.

⁴⁹ "Decarbonization challenge for steel", McKinsey, June 3, 2020

⁵⁰ "ArcelorMittal successfully tests use of green hydrogen at Canadian plant", Financial Times, May 2, 2021

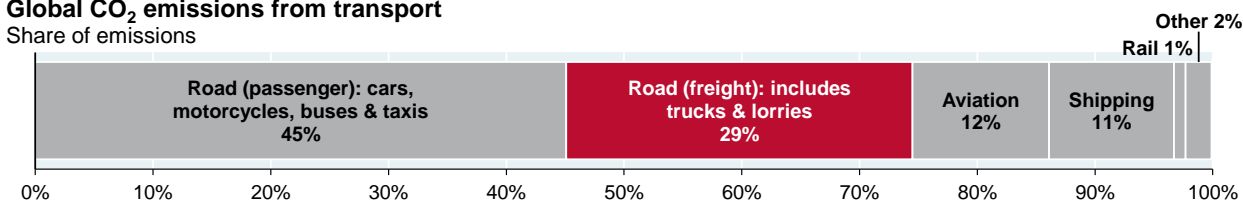


Ground transportation (trucking)

- **HO:** Trucking looks like a great hydrogen use case given faster refueling
- **MC:** Think about the two major alternatives to internal combustion engines for vehicles:
Electric: electric motor powered by a battery fueled via electricity sourced from renewable energy
Hydrogen: electric motor powered by a fuel cell whose energy is sourced from hydrogen produced via electricity sourced from renewable energy⁵¹
 So: this debate is about cost, supply chain and operational differences between EV batteries (which are rapidly improving) and hydrogen fuel cells. I don't think fuel cells are compelling for passenger vehicles given fuel tank space constraints which make their range similar to EVs⁵², but with higher energy conversion losses than EVs (see below) and less power⁵³. However, sustained EV production bottlenecks due to lithium supply chain problems are a risk to monitor. For fuel cells, platinum supply chains are more important
- **MC (continued):** Using hydrogen for long haul trucking makes a bit more sense since compressed hydrogen allows for longer range and faster refueling, and there's fewer space constraints. For example: Freightliner's pending eCascadia class 8 EV truck weighs 82,000 pounds, has a range of 250 miles and mileage of 0.5 miles per kWh. In comparison, Hyzon's pending class 8 hydrogen fuel cell truck has the same weight, but with a longer range of 375-500 miles on 50-70 kg of hydrogen (it also *might* cost less as well)
- **MC (continued):** But the word "**PENDING**" is important here since hydrogen truck companies are in their infancy and have limited track records for cost, performance, maintenance, durable lives, warranties, etc. Remember when the fuel cell truck company Nikola had its own "Theranos" moment⁵⁴? Let's wait for actual vehicle sales before making projections. Long haul trucking could be a viable use case *if* green hydrogen costs decline, and *if* fuel cell trucks are delivered as advertised. One forecast: Cummins Engine expects just 2.5% hydrogen shares in long haul heavy duty trucking by 2030⁵⁵. Timeline for adoption: medium term

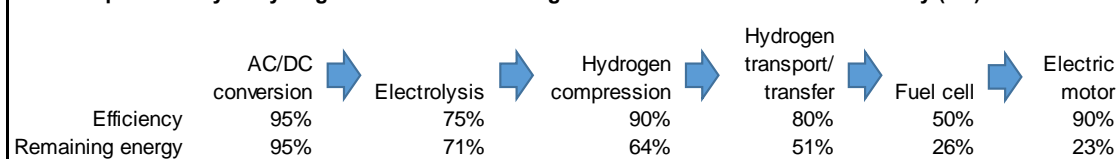
Global CO₂ emissions from transport

Share of emissions



Source: Our World in Data. 2020.

Round trip efficiency of hydrogen in vehicles: starting with 1 kWh of renewable electricity (AC)...



Source: Center for Sustainable Road Freight (UK). As a comparison, EV battery round trip efficiency = 69% assuming 10% loss from AC transmission, 15% loss for AC-DC conversion/battery charging, 10% loss from motor

⁵¹ Many fuel cell trucks also contain an electric battery to store electricity generated by the fuel cell that is not immediately used, and to recapture vehicle braking energy

⁵² A hydrogen car fuel tank cylinder that's 3 feet long and 1 foot in diameter, pressurized to 350-700 bar, would hold at most 2.8 kg of hydrogen. After fuel cell conversion losses at 50%, its effective capacity would be less than 60 kWh, compared to 100 kWh for the longest range Tesla

⁵³ Example: Toyota Mirai horsepower of 182 vs 670-1020 horsepower for Tesla Model S

⁵⁴ **SPAC-launched Nikola Motors** was fined by the SEC for staging its hydrogen truck rollout. As per Federal prosecutors, the truck's gear box was empty during the demo since Nikola didn't have a working model. The company used extension cords, winches and masking tape to create the illusion of a truck propelled by hydrogen. See "*The rise of Trevor Milton and the collapse of Nikola trucks*", MEL magazine, February 2022

⁵⁵ "*Making sense of heavy duty hydrogen fuel cell tractors*", North American Council for Freight Efficiency, 2020

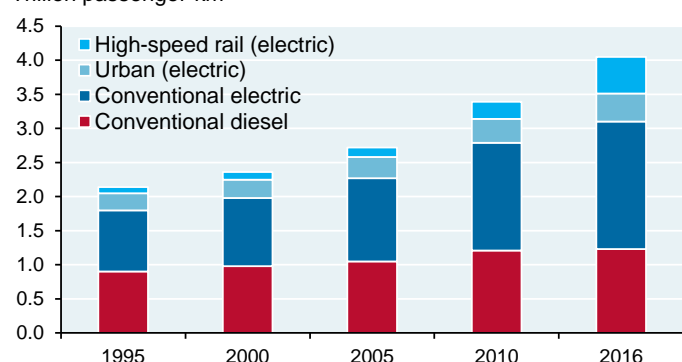


Non-electrified passenger and freight rail that still runs on diesel

- **HO:** It makes no sense to use hydrogen to power trains that are already electrified, but what about all the passenger and rail freight that still run on diesel fuel?
- **MC:** Agreed on diesel trains, since the cost of extending overhead electricity infrastructure on long corridors can be very high⁵⁶. There are hydrogen trains in operation, so proof of concept exists (China 2019, Germany Coradia iLint 2017, UK HydroFlex 2019). Alstom has an order book to provide additional fleets to operators in the UK and Germany. But let's look at the potential size of a hydrogen rail market. First, as shown below, rail only accounts for 1% of global transport emissions. And on passenger rail, 70% of global kilometers traveled were already electrified by 2016. The larger opportunity for hydrogen would be replacing diesel-powered freight, but in China, Russia and India, large portions of freight rail are already electrified as well
- **MC (continued):** The largest hydrogen opportunity would be in the US which has a very large freight rail system that is almost entirely diesel powered, and which often carries 10x the payloads of European freight trains⁵⁷. However, we see little movement on hydrogen for freight in the US, and there also might be competition from batteries. Since freight trains are already diesel-electric, a battery-electric pathway offers a cost-effective, long-term solution and could even function as a source of clean backup power⁵⁸. One of the handful of hydrogen rail projects in the US: a small San Bernardino passenger rail project scheduled for completion in 2024. Timeline for adoption: very long term

Global passenger rail transport activity by fuel type

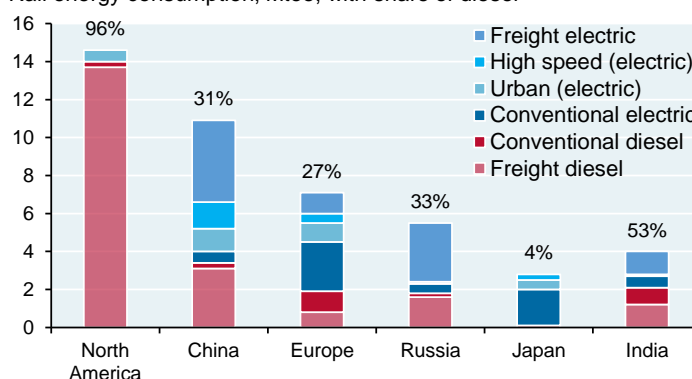
Trillion passenger-km



Source: IEA. 2019.

US freight is the largest non-electrified rail opportunity

Rail energy consumption, Mtoe, with share of diesel

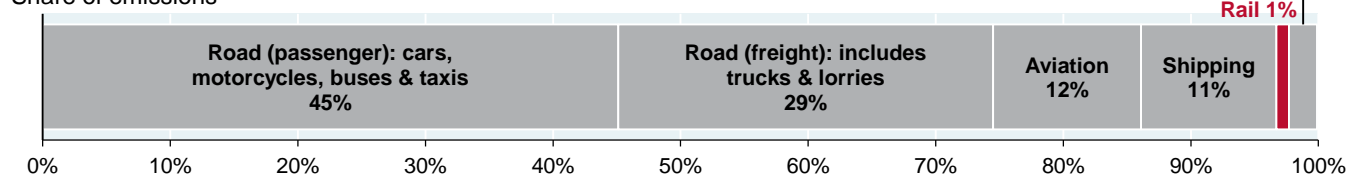


Source: IEA. January 2019.

Note: in the charts, **conventional** rail is defined as medium- to-long distance non-urban passenger train journeys with a maximum speed under 250 kilometers per hour

Global CO₂ emissions from transport

Share of emissions



Source: Our World in Data. 2020.

⁵⁶ Extension of the electricity grid to power trains via overhead lines is referred to as “catenary infrastructure”. A 2017 analysis from SINTEF research cited catenary expansion costs at 55 million Euros per year, 2.5x more than the cost of both hydrogen fuel cell and electric battery powered trains. Germany is testing **electric road systems** (overhead power lines that trucks access via overhead “pantographs”) but if SINTEF is correct, this could be a very expensive option for freight transportation

⁵⁷ “Technology Assessment: Freight locomotives”, CA EPA Air Resources Board, November 2016

⁵⁸ “Economic, environmental and grid-resilience benefits of converting diesel trains to battery-electric”, Popovich (LBNL) et al, Nature Energy, November 2021



Backup power

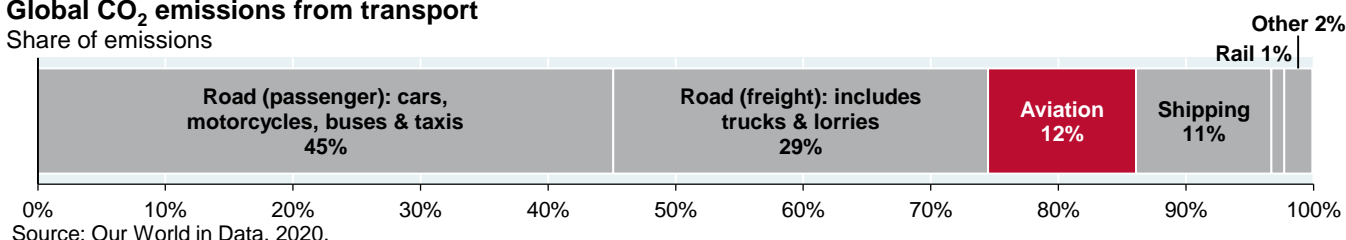
- **HO:** Well, there's always commercial back-up power demand which hydrogen can be used for
- **MC:** There are commercial back-up storage applications where hydrogen might make sense. One example is the need for wireless companies to provide more redundancy and power to remote cell tower networks as the 4G->5G transition occurs. They currently rely on diesel generators since most towers are not close to natural gas pipelines. Hydrogen storage tanks could be protected for safety purposes in these remote locations, but even here the cost per kWh could be ~2x the cost of power from existing diesel generators. Timeline for adoption: medium term but very small
- **HO:** What about residential backup power?
- **MC:** Most backup power companies offer diesel/gas generators and lithium ion batteries. There are startups offering residential hydrogen fuel cell systems. One can store 40 kWh of power, which is 3x the kWh of storage in the Tesla Powerwall. However, its power output is the same 5 kW (just enough for many central air conditioning systems), its energy efficiency is 50% compared to 85%-90% for the Powerwall, and it costs 3x more than the Powerwall before other added costs

Aviation

- **HO:** The last frontier on hydrogen is aviation. Did you see that Time Magazine called an aviation company's hydrogen technology one of the best innovations of 2020?
- **MC:** Cool your jets. That 8-minute flight on a tiny hydrogen prop plane relied on lithium batteries as well as its fuel cells, and the manufacturer reportedly had to replace four of the plane's five seats to accommodate the hydrogen storage tanks and other equipment⁵⁹
- **MC (continued):** Big picture...after accounting for hydrogen's lower fuel density (kilograms per cubic meter) and its higher gravimetric/specific energy density (joules per kilogram), a plane could hold 5.6x more jet fuel than pressurized hydrogen at 700 bars of pressure, and 3.3x more jet fuel than liquid hydrogen

Global CO₂ emissions from transport

Share of emissions



- **HO:** Anything we haven't covered?
- **MC:** There are other ideas floating around such as building dedicated nuclear plants to generate electricity used for hydrogen electrolysis; using high nuclear heat for methane pyrolysis (thermal decomposition of methane) to produce solid carbon and hydrogen; and obtaining hydrogen from water via a thermochemical cycle. We will monitor these emerging ideas to see what their all-on costs of production end up being
- **MC (continued):** One more thing. Applications that entail delivery and transport of compressed hydrogen have to be highly controlled to prevent leakage. Hydrogen is the lightest gas and can cause ozone layer reduction. There's already evidence that non-automotive hydrogen sources are rising⁶⁰. According to Environmental Defense Fund studies, higher levels of hydrogen leakage could substantially reduce the net benefits of a hydrogen economy⁶¹

⁵⁹ "ZeroAvia's hydrogen fuel cell plane ambitions clouded by technical challenges", TechCrunch, Sep 24, 2021

⁶⁰ "Researchers find 70% increase in atmospheric hydrogen over the past 150 years", Phys.org, Sep 10, 2021

⁶¹ "Climate consequences of hydrogen emissions", EDF, July 2022



Why hydrogen conclusions: a very, very long journey has just begun and some paths will be dead ends

A lot depends on how quickly costs of green hydrogen decline, the time/cost required to build electrolyzer, storage and distribution systems, *and* the time it takes for the world's machines and engines to be redesigned to use hydrogen instead. In other words, the hydrogen economy depends on more than just declining green hydrogen production costs per kg. Energy transitions are not just about learning curves and costs of energy production; the physical plant used for energy distribution and consumption have to change too.

Over the next decade, the "hydrogen economy" may entail pockets of modest demand for hydrogen used in natural gas pipeline blends, shipping/trucking, steel, commercial back-up power and non-electrified rail. If so, there may be opportunities for investors in specific hydrogen companies. But future hydrogen demand may bear little resemblance to the explosive hockey-stick growth forecasts common in today's renewable energy literature... and in the energy literature of the past as well (see below).

Hydrogen has a long history of being right around the corner

"Hydrogen economy: A practical answer to problems of energy supply and pollution" (*Science*, 1972)

"Hydrogen: Its Future Role in the Nation's Energy Economy" (*Science*, 1973)

"Clean hydrogen beckons aviation engineers" (*New York Times*, May, 1988)

"Hydrogen economy in the future" (*International Journal of Hydrogen*, 1999)

"Amory Lovins Sees the Future and It Is Hydrogen" (*Grist*, May 1999)

"The Hydrogen Economy" (Jeremy Rifkin, 2003)

Summary statistics for the Hydrogen Economy

Description	
Global CCS as % of global emissions, 2021	0.1%
Emissions potential of US and European CCS projects under development as % of regional emissions	1%-2%
Nordic share of steel production, 2020	0.5%
Conversion losses from natural gas to hydrogen using Steam Methane Reforming (SMR)	30%
Energy conversion losses from Alkaline and PEM electrolysis (energy value of hydrogen produced as a percentage of the energy in the electricity used)	25%-35%
Fuel cell efficiency (in conversion of hydrogen to electricity)	50%-60%
Round trip efficiency of fuel cells in transportation	25%
Round trip efficiency of hydrogen in transportation when liquefaction, shipping and regasification required	15%-30%
Round trip efficiency of liquid ammonia produced from green hydrogen for shipping	11%-19%
Energy lost in liquefaction of gaseous hydrogen into liquid hydrogen	30%-40%
Global enhanced oil recovery demand for CO ₂ as % of global CO ₂ emissions	0.2%

Sources: Argonne National Labs, National Renewable Energy Laboratory, Global CCS Institute, Clean Air Task Force, ICCT, ACS Energy Letters, Center for Sustainable Road Freight, University of Cambridge, BP, World Steel Association, Goldman Sachs, JPMAM, 2022.

Hydrogen color spectrum

Green: hydrogen produced by electrolysis of water, using electricity from renewable sources like hydropower, wind, and solar. Zero carbon emissions are produced	Turquoise: hydrogen produced by the thermal splitting of methane. Instead of CO ₂ , solid carbon is produced
Pink/purple/red: Hydrogen produced by electrolysis using nuclear power	Black/gray: hydrogen extracted from natural gas using steam-methane reforming
Yellow: hydrogen produced by electrolysis using grid electricity	Blue: gray or brown hydrogen with its CO ₂ sequestered or repurposed
White: hydrogen produced as a byproduct of industrial processes (i.e. fracking)	Brown: hydrogen extracted from fossil fuels, usually coal, using gasification

Source: North American Council for Freight Efficiency. 2020.

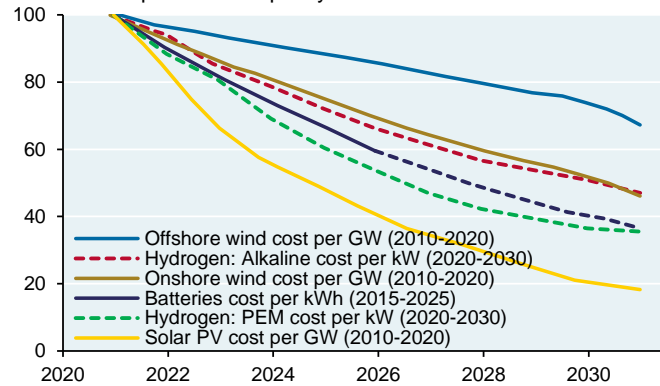


Why hydrogen exhibits

Current green hydrogen production is negligible but some researchers project increases due to falling costs of electrolysis. Goldman's recent report⁶² is one example; they assume that prior learning curves apply to hydrogen, in which case its levelized cost could converge with blue hydrogen (which also doesn't really exist today at commercial scale) and with grey hydrogen by the end of the decade.

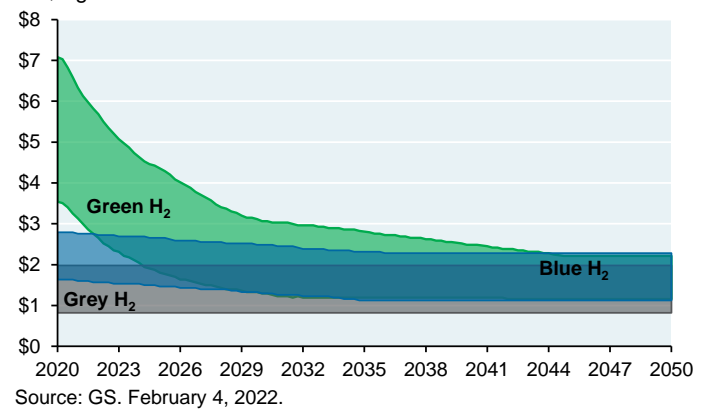
Learning curves

Indexed cost per unit of capacity



Hydrogen levelized cost projections

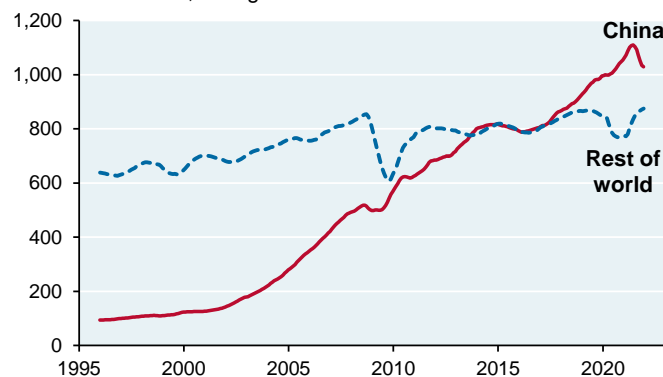
US\$/kg



China's dominance in global steel production:

Crude steel production: China vs rest of world

Million metric tons, rolling 12 month sum



⁶²"Carbonomics: The clean hydrogen revolution", Goldman Sachs, February 2022



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