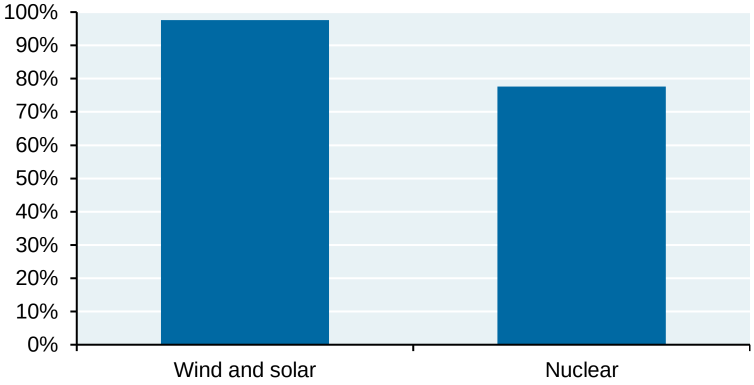
Whydrogen? Expanded use cases for hydrogen may be narrower than advertised, and the timeline is long

In our 2022 energy paper, we included a section called "Whydrogen" to review the gap between the enthusiasm for new hydrogen use cases and the thermodynamic challenges they face. We have been updating this section with new information as it becomes available. Our original views are unchanged: while there might be opportunities to replace some existing "brown/grey" hydrogen with "green" hydrogen, the amounts are likely to be small given the energy intensity of electrolysis; and the new use cases will evolve very slowly, if at all.

On the former, consider this chart. How energy intensive is electrolysis as a means of producing hydrogen? To replace existing brown/grey hydrogen with green electrolyzed hydrogen (assuming 52.5 kWh per kg), it would take all current US wind and solar generation or ~80% of US nuclear generation to provide the power needed.

Share of renewable or nuclear generation required to replace US brown hydrogen with green hydrogen



Source: JPMAM calculations, EI Statistical Review of World Energy, IPST, NREL, IEA, NextEra. 2023.

In recent months, there have been a few hydrogen project cancellations in Europe and the US which were related to transportation and agriculture. As true costs and all-in efficiencies of these projects became clearer, the public and private sector entities involved terminated them. The remainder of this document includes our updated long-form discussion of hydrogen production, distribution and consumption and the long road ahead.

Hydrogen project cancellations:

- Liverpool: 20 hydrogen buses (unreliable H2 supply, and hydrogen was grey not green)
- ATCO: 10 MW electrolyzer (distance between production and end use undermined commercial viability)
- Germany: hydrogen fuel-cell powered train system (opting for battery-electric models instead)
- Glasgow: contract to purchase 19 hydrogen-power trucks (opting for battery-electric vehicles instead)
- France/Montpellier: 51 hydrogen buses powered by solar-powered green hydrogen plant (mayor noted that hydrogen buses were "six times more expensive than electric buses" to operate)
- Fertilizer manufacturer Nutrie: 1.2 mm tonne/yr blue hydrogen-based ammonia plant (uncertain demand)
- Electrolyzer manufacturers downgrading plans to expand production capacity for the first time since 2021, on the back of policy hold-ups and a backlog of green hydrogen projects unwilling to commit to firm orders

Whydrogen? Expanded use cases for hydrogen may be narrower than advertised, and the timeline is long

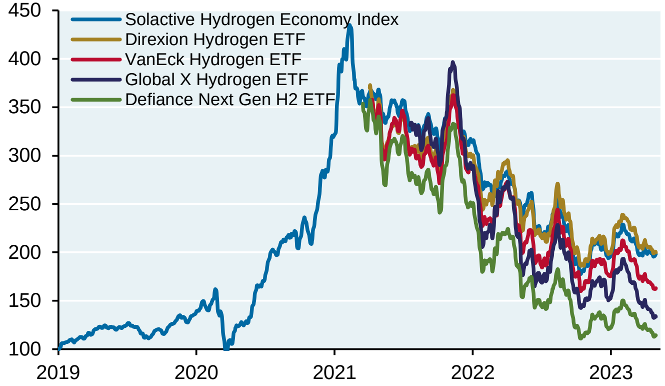
To be clear, there is already a "hydrogen economy". As shown in the second chart, ~124 million metric tons of hydrogen are consumed each year mostly to produce ammonia for fertilizer, to reduce the sulfur content of diesel fuel in oil refining and to produce methanol. Smaller amounts are also used to produce iron and steel using hydrogen as an iron ore reducing agent alongside carbon monoxide. Around 94 million tonnes of this hydrogen are produced directly, while ~30 million tonnes are sourced from residual gases derived from industrial processes used for heat and electricity generation. As a reminder, 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 2000.

In other words, almost no hydrogen is used in power, transport, home heating, sea-borne shipping, trucking, rail, aviation or other widely discussed use cases. And: practically all hydrogen is created via steam reformation of fossil fuels, with less than 1% created via electrolysis using renewable energy (green hydrogen).

If green hydrogen ever replaced existing hydrogen produced via fossil fuels, that would be a substantial climate achievement; but it would also require new dedicated green electricity that's even greater in MWh terms than current global wind and solar generation[1]. As difficult as this would be, hydrogen advocates expect even more, anticipating many of the other use cases cited above. I got into a discussion with some hydrogen optimists (HO) recently about all of this. This section is a synopsis of that discussion.

The performance of hydrogen linked equities

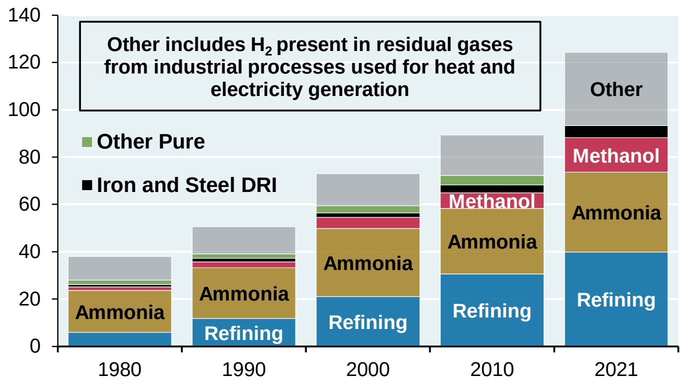
Index (100 = Jan 2019), 3 day smooth



Source: Bloomberg, JPMAM. May 3, 2023.

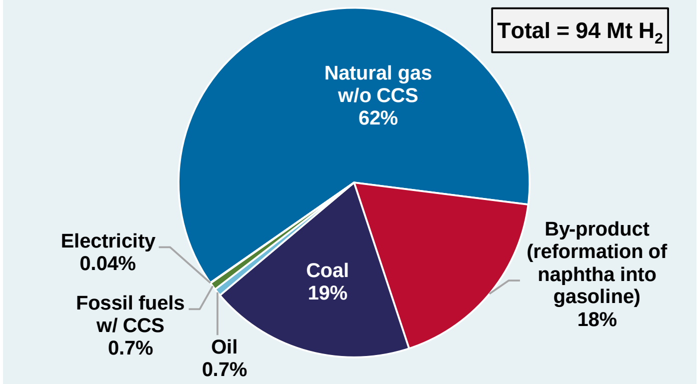
Global annual consumption of hydrogen since 1980

Million metric tons



Source: IEA. 2022.

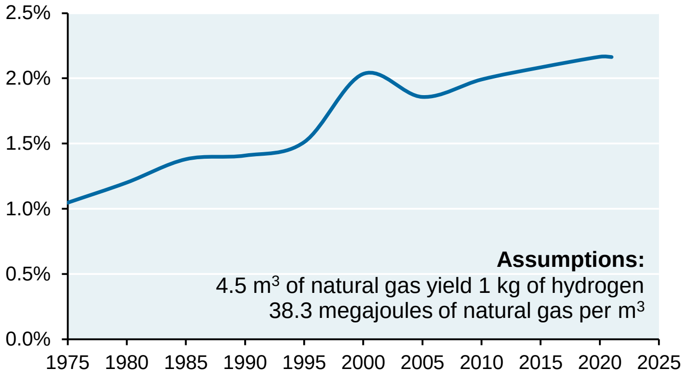
Energy sources used to create hydrogen



Source: IEA. 2022. CCS = Carbon capture & storage. Note: excludes 30 Mt in residual gases from industrial processes used for heat & electricity generation.

Share of global primary energy used to create hydrogen

%



Source: IEA, S&P Global, BP, NREL, JPMAM. 2022.

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[1] Assuming 60% conversion efficiency for liquid alkaline and PEM electrolyzers, 1 kg of hydrogen requires ~55 kWh of electricity inputs. As a result, 5,170 dedicated TWh of green electricity (~180% of 2021 global wind and solar generation) would be needed to produce 94 million metric tons of green hydrogen.

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

Natural gas field compressors and grey hydrogen energy math

- **HO**: Let's start here: in the US, 25,000 upstream, midstream and downstream natural gas field compressors account for 2%-3% of US natural gas consumption[2]. 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* CO_2 emissions compared to using natural gas directly due to the ~30% losses involved in the conversion of natural gas to hydrogen[3] (and which would increase CO_2 emissions by 43% assuming 70% low heating value (LHV) efficiency in hydrogen production)

Pipeline blending

- **HO**: What about midstream companies considering hydrogen blends in existing natural gas pipelines?
- **MC**: Again, that only makes sense if they were to use "green" hydrogen produced via electrolysis powered by renewable energy. In other words, it would make no sense to blend grey hydrogen into natural gas pipelines given the increase in CO_2 emissions that would entail (applying the same logic above with respect to pipeline field compressors). There's also the question of whether natural gas pipelines can physically *withstand* a lot of hydrogen

- **HO**: There are already pilot projects underway, and so far the pipelines are performing well
- **MC**: So far so good. Pipeline engineers have to look for "embrittlement" which refers to cracking and other pipeline degradation. Valves, flanges, compressors and tubes need to be retested given the presence of hydrogen, and at blend rates over 10% some equipment might have to be replaced. National Grid announced a project on Long Island to blend up to 20% green hydrogen into its natural gas system, and intends to expand it to other places in the Northeast[4]. Pilot programs have also been launched in Scotland, Australia, Colorado and California. Timeline for adoption: medium term
- **MC (continued)**: A piece just came out from the International Renewable Energy Agency (IRENA) that is also highly critical of pipeline blending: they estimate that blending green hydrogen with natural gas achieves very limited CO_2 reductions at a very high cost of $500 per ton of CO_2. A German think tank went further, claiming that green hydrogen blending with gas could increase home heating costs by 33% by 2030

Blue hydrogen and commercial demand for CO_2

- **HO**: What if these field compressors and pipeline blends used "blue" hydrogen instead, which refers to grey hydrogen production combined with geologic sequestration of CO_2 via carbon capture and storage (CCS)?
- **MC**: CCS has been the most overhyped industrial process in the modern era, with hundreds of academic papers written and still just 0.1% of global CO_2 emissions are sequestered underground. Europe is forging ahead with 76 CCS projects, mostly dedicated to enhanced oil recovery (EOR)[5]. Even so, Europe's sequestration potential from these projects in 2030 is 50 million metric tons per year of CO_2, which is 1% of its annual emissions. US sequestration potential from projects under development also amount to less than 2% of US CO_2 emissions[6]. Similarly, McKinsey estimated that global sequestration may only reach 1% of global emissions in 2030, and that's with supportive policies in place[7]. The CCS infrastructure required for a more substantial impact would be enormous, and rival the size of existing oil pipeline infrastructure[8]. By the way, recent research has thrown cold water on the climate benefits of blue hydrogen production

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[2] "*US Natural Gas Compression Infrastructure: Opportunities for Efficiency Improvements*", Ebara Corp, 2018

[3] "*Updates of Hydrogen Production from SMR Process*", Argonne National Labs, 2019

[4] "*Can Green Hydrogen Clean Up Natural Gas?*", Bloomberg City Lab, December 21, 2021

[5] "*CCUS In Europe*", IFRI Center for Energy & Climate, August 25, 2021 and Global CCS Institute

[6] *"Global Status of CCS 2021"*, Global CCS Institute, October 2021

[7] "*Driving CO_2 emissions to zero (and beyond) with carbon capture, use and storage*", McKinsey, June 2020

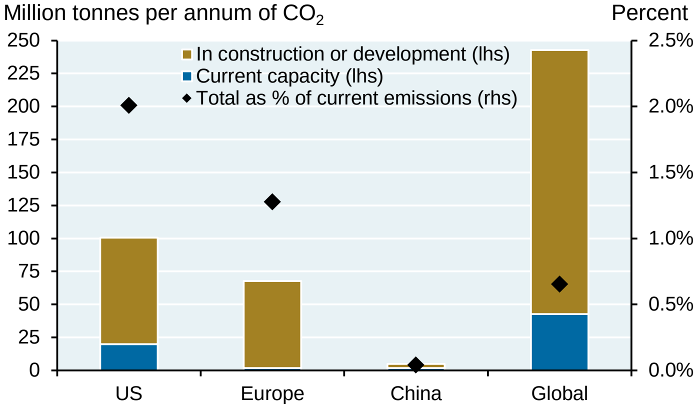
[8] See "*Future shock*", annual energy Eye on the Market, 2021, page 22

- **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 directly[9], due to additional energy demands of CCS, a typical capture rate that's well below 100% and the energy intensity of grey hydrogen production
- **MC (continued)**: The bottom line on blue hydrogen…you need all of these to make it work:
  [a] A very high capture rate of CO_2 from syngas
  [b] A process to also capture the CO_2 from hydrogen purification steps downstream
  [c] Very low leakage rates in natural gas production and distribution systems
  [d] Renewable energy to run all the capture equipment
  [e] Proximity to a permeable reservoir for CO_2 disposal

- **HO**: What if there were growth in commercial demand for the CO_2 that grey hydrogen produces? CO_2 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 CO_2. It's only used in 2.5% of US crude oil production, and global EOR consumption of CO_2 in 2019 was just 72 million metric tons, which is 0.2% of global emissions. McKinsey cites potential CO_2 demand of 10,700 million metric tons in 2030 from producers of synthetic and algae based fuels[10], but that's another one of those "anything could happen" renewable energy forecasts which have little basis in currently commercialized fuel systems
- **MC (continued)**: The very thing that makes CO_2 a desirable byproduct of energy producing reactions (low potential chemical energy) makes it a terrible feedstock from which to make much of anything. Also, most CO_2 uses today result in that CO2 ending up back in the atmosphere (urea, beverage carbonation)

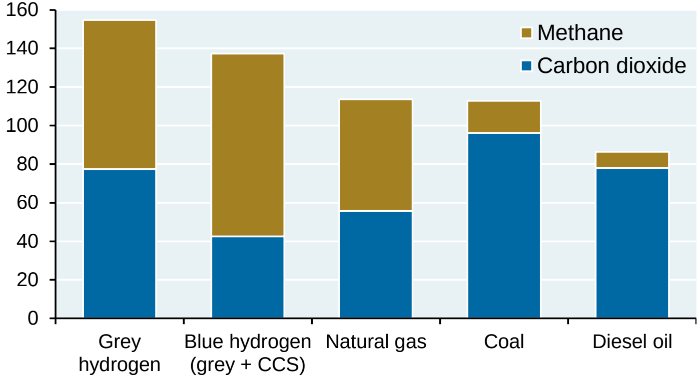
- **HO**: Existing CCS distribution networks are small, but what if large portions of the US natural gas pipeline network were repurposed for carbon instead once enough wind and solar exist?
- **MC**: I cannot envision such a thing taking place in my lifetime, and I am 60

Current vs planned carbon sequestration by 2030



Source: Global CCS Institute, OWID, JPMAM. 2022.

Blue hydrogen GHG higher than direct natural gas combustion, Grams of CO_2 equivalent per MJ of energy



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

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[9] *"How green is blue hydrogen?"*, Robert Howarth et al, Energy Science Engineering, 2021

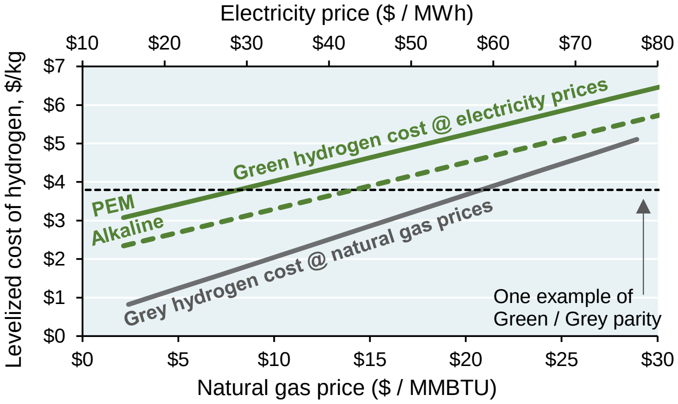
[10] *"Driving CO_2 emissions to zero (and beyond) with carbon capture, use and storage"*, McKinsey, June 2020

Green hydrogen costs

- **HO**: OK, so let's talk about green hydrogen costs. Goldman projects steep declines in electrolysis costs that are similar to those achieved during prior learning curves on wind, solar and batteries
- **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 PEM[11] electrolyzers paying $30 per MWh for wind and solar power (European PPAs are $5-$10 higher than that right now[12] 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 in May 2022 priced in a 33% decline by April 2024
- **MC (continued)**: I saw a chart in a hydrogen report entitled "Green H_2 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

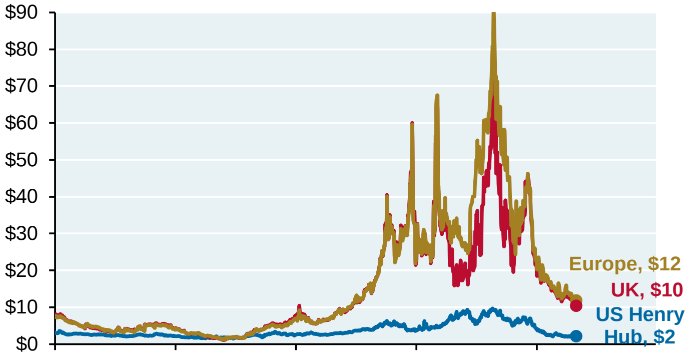
Green vs Grey hydrogen costs as a function of fuel costs



Source: Goldman Sachs Carbonomics data, JPMAM. 2022.

The US-Europe natural gas gap

Wholesale natural gas price, US$ per MMBTU



Source: Bloomberg, JPMAM. May 3, 2023.

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

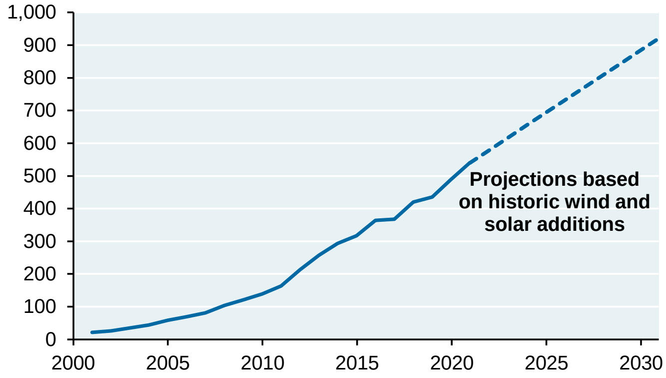
[12] Source: Level Ten Energy Q4 2021 PPA P25 Index. **Breakeven dynamics will be more challenging for hydrogen producers paying industrial rather than wholesale prices for electricity**. For example, US wholesale electricity prices averaged 5.6 cents per kWh in 2021 while industrial prices averaged 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, and a very ambitious 40 GW target for 2030 (which may be hard to meet given the lack of adequate electrolyzer manufacturing capacity). If all 6 million metric tons of green hydrogen from this 40 GW[13] were used for oil refining, that could 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, green hydrogen projects get the process started but are not transformative. And: where will all the green electricity come from for these electrolyzers??
- **MC (continued):** 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 2030[14] 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

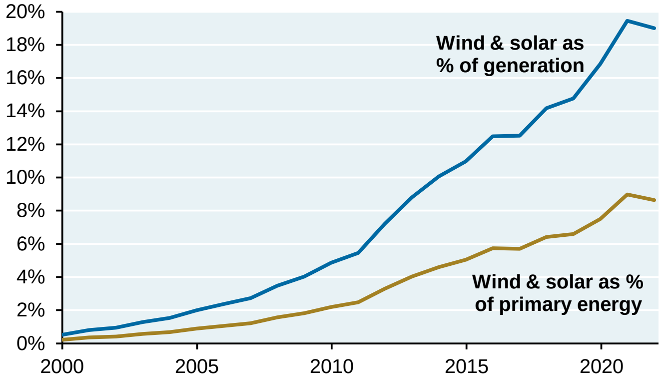
Terawatt hours



Source: Ember, Agora Energiewende. 2021.

European Union wind and solar energy

Percent



Source: BP Statistical Review of World Energy, JPMAM. 2022.

- **HO:** Don't forget about the green hydrogen that Europe plans to import as well
- **MC:** Germany entered into a partnership with companies in the UAE to provide green hydrogen, possibly shipped in liquid form via Liquid Organic Hydrogen Carriers 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

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[13] 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%.

[14] "*EU Power Section in 2020*", Ember Climate research

Long haul shipping using hydrogen or ammonia as fuel

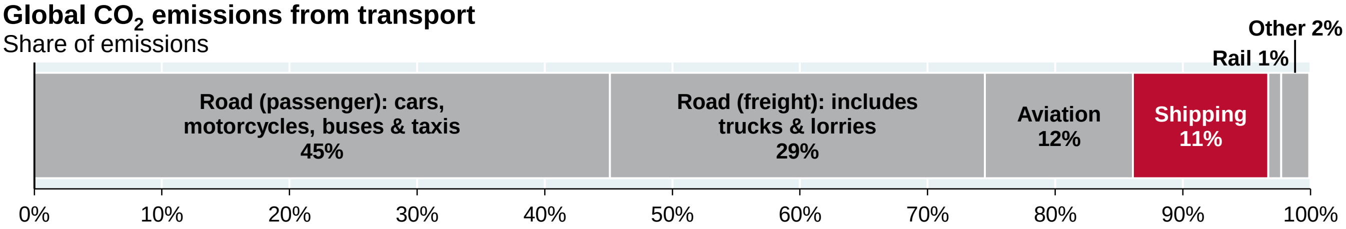
- **HO**: Shifting gears for a minute, there's definitely potential for hydrogen as a fuel for long haul shipping
- **MC:** One thing's for sure: lithium ion batteries are nonsensical for shipping given cost and energy density constraints. Using state of the art electric batteries with 300 Wh/kg of energy density, an electric version of Maersk's Triple-E class containership might require 40% of its cargo capacity for batteries[15]. 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 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). Shipping companies have highlighted development issues that need to be resolved: safety of cryogenic liquid hydrogen, leakage/detonation risks and the need for new bunkering infrastructure[16]. *Energy Environmental Sciences* highlights the challenge: there is no hydrogen storage solution that combines high energy density, low energy input, is easily available and is easy to handle and store[17]

- **HO:** The challenges with hydrogen as a shipping fuel have led some companies to focus on using ammonia 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 network[18], 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%[19], even lower than ICE engines at ~25%. Timeline for adoption: long
- **MC (continued):** One last thing. A chemical engineer with three decades of experience told me that ammonia use in shipping "terrifies him" given the risks of using ammonia in confined spaces

Global CO_2 emissions from transport

Share of emissions



Source: Our World in Data. 2020.

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[15] "*Electric container ships are a hard sail*", Vaclav Smil, IEEE Spectrum March 2019:22

[16] "*Five lessons to learn on hydrogen as ship fuel*", DNV Maritime, September 2021

[17] *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

[18] 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

[19] *"H_2 and NH_3 – 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)[20]. 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 ton[21]

- **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 catalysts[22]. 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 H_2 DRI-EAF, Direct Reduced Iron/Electric Arc Furnace)[23]. Some estimates show decarbonization potential of 70%[24]
- **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 exhausted[25]. 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 H_2 DRI-EAF process. But only 7% of the natural gas normally used in the DRI process was replaced, and it's still a demonstration project[26]. Timeline for adoption: long term, negligible global impact without China

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[20] "*Is ammonia the fuel of the future?*", Petrochemicals Magazine, March 8, 2021

[21] "*Large investments, high renewable power costs challenge green ammonia*", IHS Markit, August 13, 2021

[22] *"H_2 and NH_3 – the Perfect Marriage in a Carbon-free Society",* El Kadi et al (Univ. of Cambridge), May 2020

[23] "*Hydrogen in steel production: what is happening in Europe*", Bellona Climate Foundation (Oslo), May 2021

[24] "*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.

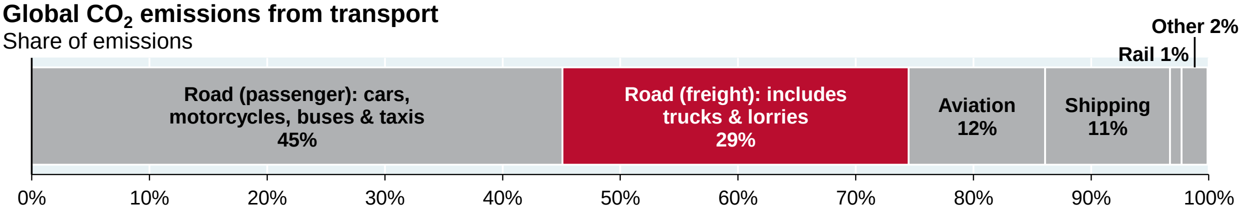
[25] "*Decarbonization challenge for steel*", McKinsey, June 3, 2020

[26] *"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 energy[27]
  So: this debate is about cost, supply chain and operational differences between EV batteries (which are rapidly improving) and hydrogen fuel cells. Fuel cells don't make sense for passenger vehicles given fuel tank space constraints which make their range similar to EVs[28], but with higher energy conversion losses than EVs (see below) and less power[29]
- **MC (continued):** EVs for medium range trips is gaining traction; lithium supply chains and charging stations will eventually improve, and the weight issue is mitigated by the fact that most trucking runs are not close to their gross vehicle weight limits, based on data from the North American Council for Freight Efficiency. In other words, battery weight is typically less of a constraint than you might think
- **MC (continued):** Hydrogen for trucking might make sense as well since compressed hydrogen could allow for longer range and faster refueling, and there's fewer space constraints. But hydrogen charging stations are more complicated than EV counterparts given the need for chillers to prevent overheating
- **MC (continued)**: Last point. 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 "Theranos" moment[30]? 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 2030[31]. Timeline for adoption: medium term

Global CO_2 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)...

	AC/DC conversion	Electrolysis	Hydrogen compression	Hydrogen transport/ transfer	Fuel cell	Electric motor
Efficiency	95%	75%	90%	80%	50%	90%
Remaining energy	95%	71%	64%	51%	26%	23%

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

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[27] 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

[28] 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

[29] Example: Toyota Mirai horsepower of 182 vs 670-1020 horsepower for Tesla Model S

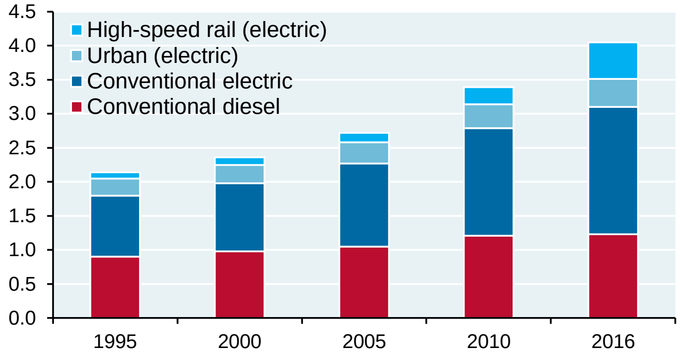
[30] **SPAC-launched Nikola Motors** was fined by the SEC for staging its hydrogen truck rollout. As per Federal prosecutors, the truck's gear box was empty during the demo since Nikola didn't have a working model. The company used extension cords, winches and masking tape to create the illusion of a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

[31] "*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

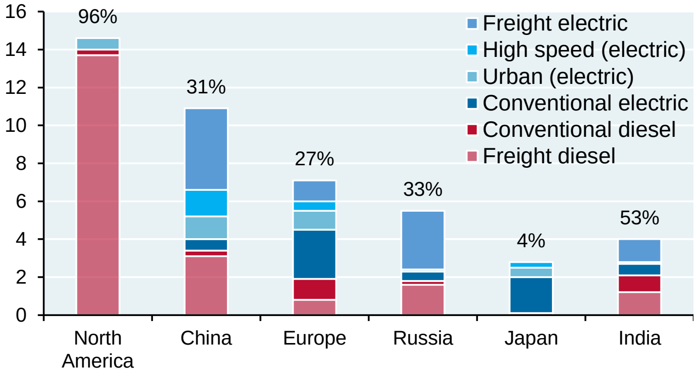
- **HO:** It makes no sense to use hydrogen to power trains that are already electrified, but what about all the passenger and rail freight that still run on diesel fuel?
- **MC**: Agreed on diesel trains, since the cost of extending overhead electricity infrastructure on long corridors can be very high[32]. 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 rail 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 trains[33]. 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 power[34]. 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, and will eventually compete with biofuels

Global passenger rail transport activity by fuel type
Trillion passenger-km



Source: IEA. 2019.

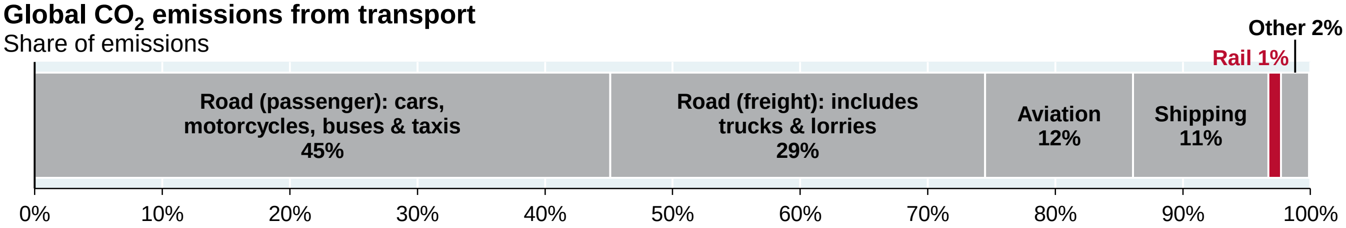
US freight is the largest non-electrified rail opportunity
Rail energy consumption, Mtoe, with share of diesel



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 CO_2 emissions from transport
Share of emissions



Source: Our World in Data. 2020.

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[32] 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

[33] *"Technology Assessment: Freight locomotives"*, CA EPA Air Resources Board, November 2016

[34] "*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 impact

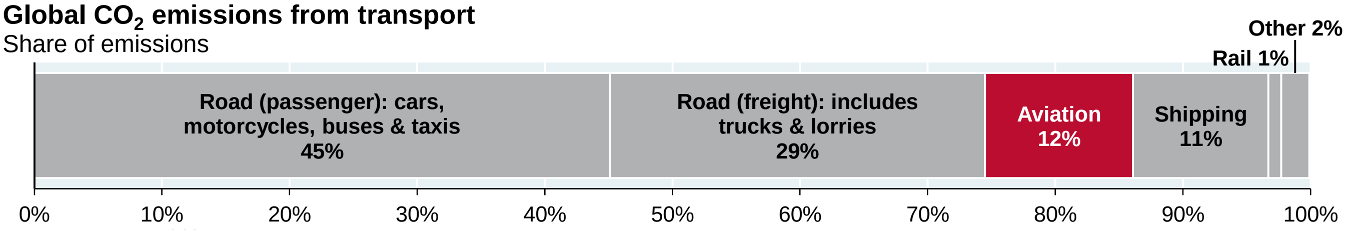
- **HO**: What about residential backup power?
- **MC**: Most backup power companies offer diesel/gas generators and lithium ion batteries. There are startups offering residential hydrogen fuel cell systems. One can store 40 kWh of power, which is 3x the kWh of storage in the Tesla Powerwall. However, 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 equipment[35]
- **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 CO$_2$ emissions from transport

Share of emissions



Source: Our World in Data. 2020.

- **HO**: Anything we haven’t covered?
- **MC**: There are other ideas such as building dedicated nuclear plants to generate electricity for hydrogen electrolysis; using high nuclear heat for methane pyrolysis (thermal decomposition of methane) to produce solid carbon and hydrogen (see Appendix); 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 rising[36]. According to Environmental Defense Fund studies, higher levels of hydrogen leakage could substantially reduce the net benefits of a hydrogen economy[37]

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[35] “*ZeroAvia’s hydrogen fuel cell plane ambitions clouded by technical challenges*”, TechCrunch, Sep 24, 2021

[36] “*Researchers find 70% increase in atmospheric hydrogen over the past 150 years*”, Phys.org, Sep 10, 2021

[37] “*Climate consequences of hydrogen emissions*”, EDF, July 2022

Whydrogen conclusions: a 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. But future hydrogen demand may bear little resemblance to the explosive hockey-stick growth forecasts common in today's renewable energy literature, and in energy literature of the past as well. **Replacing existing brown hydrogen with green hydrogen via electrolysis is ambitious enough**; as explained on page 1, this would require way more dedicated wind and solar power than the world generates today.

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 Reformation (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.

A note on turquoise hydrogen: methane pyrolysis as an alternative to steam methane reformation

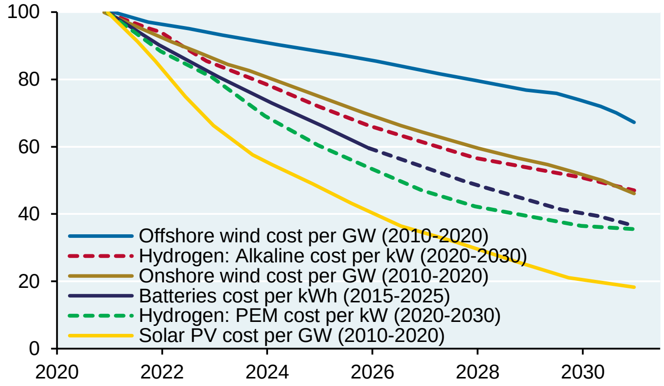
We have not discussed methane pyrolysis, which is an alternative to steam methane reformation of natural gas as a means of producing hydrogen. In pyrolysis, methane is spit into hydrogen and solid carbon using thermal decomposition at very high temperatures; the required heat or energy could in principle be zero-carbon renewable or nuclear power. Companies like Monolith are working on pyrolytic hydrogen and received a $1 billion loan guarantee from the Department of Energy.

The pyrolysis challenge: 3x more carbon by mass is produced than hydrogen. Assuming that all 94 million metric tons of existing global hydrogen production were created using this approach, the amount of carbon black created would be ~270 million metric tons, which is 1-2 orders of magnitude larger than demand for carbon black today [ARPA, 2021]. ARPA has held workshops on the premise of using carbon black as a reinforcing filler to complement steel in construction, and to create products akin to plastic PVC pipes. But as things stand now, the limited market for carbon byproducts may constrain the scope of pyrolytic production of hydrogen.

Whydrogen exhibits

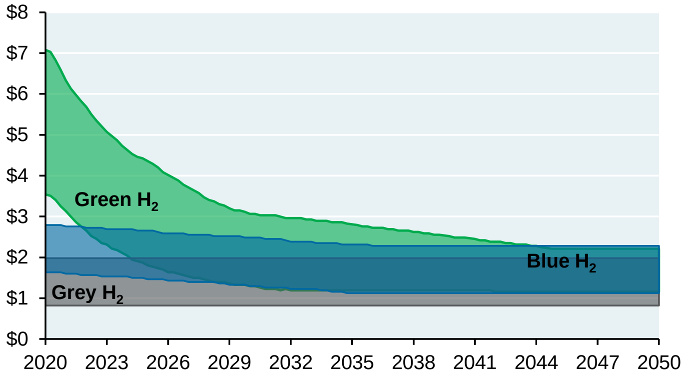
Current green hydrogen production is negligible but some researchers project increases due to falling costs of electrolysis. Goldman's report[38] is one example; they assume that prior learning curves apply to hydrogen, in which case its levelized cost could converge with blue hydrogen (which also doesn't really exist today at commercial scale) and with grey hydrogen by the end of the decade.

Learning curves
Indexed cost per unit of capacity



Source: GS. February 4, 2022. Dotted lines indicate estimates.

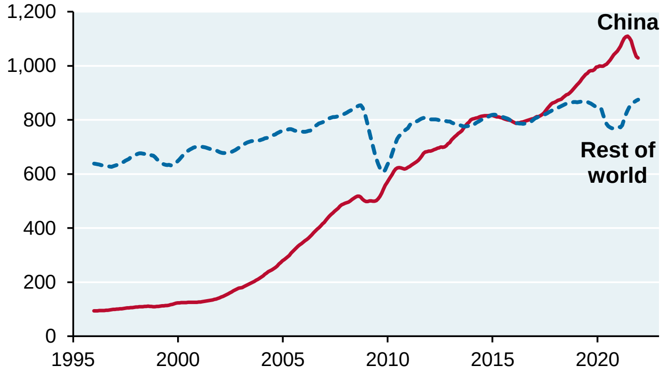
Hydrogen levelized cost projections
US$/kg



Source: GS. February 4, 2022.

China's dominance in global steel production:

Crude steel production: China vs rest of world
MIllion metric tons, rolling 12 month sum



Source: Bloomberg, JPMAM. March 2022.

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[38] *"Carbonomics: The clean hydrogen revolution"*, Goldman Sachs, February 2022

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