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Hydrogen – will it power mobility and transport in the 21st century?

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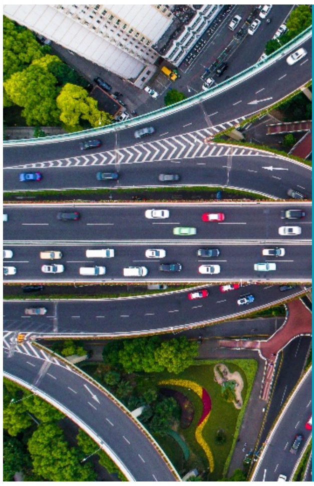

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Summary

Hydrogen as an energy carrier has experienced a surge in attention from corporations, governments, investors, and the general public. This attention is well justified, as clean hydrogen has the potential to significantly advance decarbonization efforts in many sectors. Our focus here is on the viability of hydrogen for road transport, and we consider sustainability, technological, and end-use perspectives.

We find that, while fuel cell electric vehicles (FCEVs), powered by hydrogen, have the potential to reduce greenhouse gas emissions in road transportation, other options such as battery electric vehicles (BEVs) or electrified railway transport are equally beneficial and economically more viable alternatives. Interesting exceptions, where fuel cells have clear advantages over their battery-powered counterparts, are forklifts for inventory warehousing and fuel cell trucks for long-haul freight.

Though hydrogen has significant potential for reducing emissions in other heavy-emitting sectors, it also faces significant obstacles related to production, transmission, and distribution that must be overcome before its promise translates to reality. The decade ahead will be critical for revealing how quickly hydrogen technologies can develop to surmount these challenges.

Introduction

Hydrogen is already used in many industrial applications, from oil refining and steel production to chemical and fertilizer manufacturing. Global demand for pure[1] and blended forms of hydrogen reached 120 million tons in 2019, and other sectors are also considering hydrogen to replace fossil fuels. The timelines of these transitions vary from a few years to several decades.

Road transportation is one sector where transition appears imminent. Transportation accounts for 16% of total global greenhouse gas emissions, with values that reach 28% in developed countries such as the US. Furthermore, it is estimated that road transportation emissions will continue to grow until 2030 before reaching a tipping point. For this reason, finding carbon neutral alternatives is paramount for reaching carbon neutrality by 2050.

With its promise of zero carbon emissions, hydrogen-powered transportation is in the spotlight. But is all the excitement warranted? Do hydrogen solutions surpass and should they displace decarbonizing alternatives already on the market?

[1] Road transportation applications require pure hydrogen, i.e. not mixed with natural gas or other substances.

Technology

Fuel cells and storage

Fuel cell technology is clean but expensive. Storage of hydrogen used as fuel is also complex, significantly reducing its cost-competitiveness compared to other fuel sources.

Fuel cells

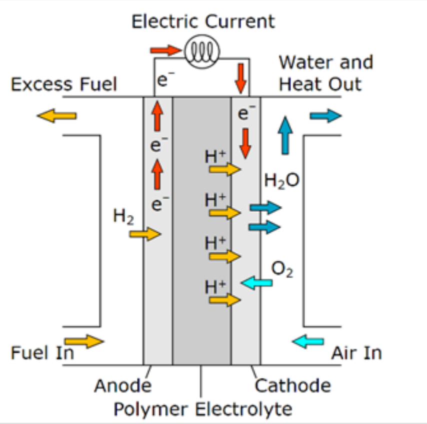
A fuel cell generates electricity through an electrochemical reaction. Within a hydrogen fuel cell, hydrogen gas (H_2) is introduced at one end of the cell where an anode strips its atoms of their negatively charged electrons (e^-) which are then forced through a circuit to produce an electrical current. The resulting positively charged hydrogen ions (H^+) then pass through the electrolyte membrane towards the cathode.

After passing through the electric circuit, the electrons are re-combined with the hydrogen ions and oxygen (O_2) from air pumped in at the opposite end of the fuel cell. The resulting product is electricity, with water (H_2O) and heat as byproducts (see Figure 1).

There are many types of fuel cell technology that vary based on what electrolyte, operating temperature and/or catalyst are used. Proton Exchange Membrane fuel cells, or PEMs, are the most common found in road transport vehicles and offer many advantages, such as low operating temperatures and the use of air as an oxidant.

A perceived disadvantage of fuel cells is the use of platinum as a catalyst to facilitate the process of extracting electrons from hydrogen gas. Platinum is a rare and expensive metal, which increases manufacturing costs. However, platinum use will eventually decrease as new alloys and alternative materials are explored for fuel cell vehicle applications. Several manufacturers have announced plans to start production of platinum-light fuel cells.

Figure 1   How a fuel cell works



A fuel cell combines hydrogen fuel (H_2) with oxygen (O_2) from the air to produce an electrical current with the help of an electrolyte (here a proton exchange membrane, or PEM). The product is electricity and byproducts are water (H_2O) and heat.

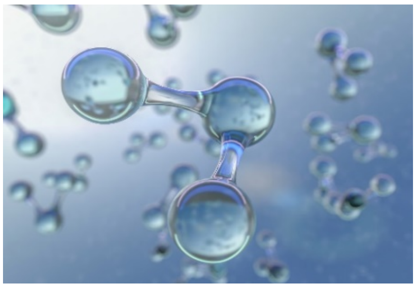
Source: Wikimedia Commons

Storage tanks

Another integral part of fuel cell powered vehicles is the storage tank for hydrogen fuel. There are several technologies available for hydrogen storage, some of which require high pressurization of hydrogen gas or even its liquification at extreme sub-zero temperatures. In the next ten years the more commercially and technologically viable solution for most applications appears to be pressurized tanks. Still, some automakers believe liquification is the way forward. In the long-haul trucking sector, Daimler is planning to develop trucks running on liquid hydrogen by the second half of the 2020s.

Tanks represent a significant design and commercial challenge for manufacturers, as they are costly to produce and occupy a large volume of the vehicle frame. Fuel cell advocates argue that hydrogen is a very efficient energy carrier, having a mass energy density three times higher than diesel. This means that 1kg of hydrogen holds three times more energy than 1kg of diesel. The problem, however, lies in volumetric density.

It takes a lot of external pressure (and energy) to concentrate hydrogen into the volumes needed to come even close to diesel on an energy-per-volume scale; and diesel still wins by a long shot. One liter of hydrogen at standard gas tank pressure contains almost eight times less than diesel. Even if the higher tank-to-wheel efficiency[2] of hydrogen drivetrains compared to diesel vehicles is considered, fuel cell vehicles would still require four to seven times more storage than current diesel tanks.


An artistic rendering of hydrogen gas illustrating its low density by volume.

Source: Getty images

Liquified hydrogen

Liquified hydrogen improves hydrogen's density-to-volume ratio so that more energy can be stored in smaller containers. One liter of pure, subcooled liquid hydrogen contains nearly four times less energy than diesel. But liquification has its own problems. Given that liquefied hydrogen requires thick walls to ensure insulation and a cylindrical shape to ensure robustness, fuel cell electric vehicles running on liquified hydrogen would still require at least four times the storage volume of current diesel trucks. In addition, liquid hydrogen is subject to boil-off, the return to a gaseous state due to inefficiencies in insulation. Boiled-off hydrogen means not only lost fuel but also increased pollution, as hydrogen is an indirect greenhouse gas.

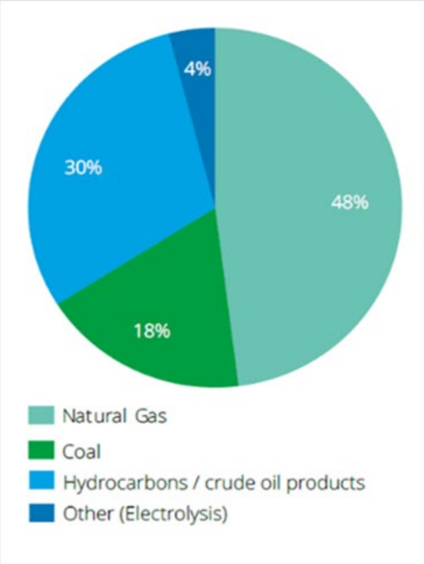
Is hydrogen fuel sustainable?

Hydrogen (like electricity) is not an energy source, but rather an energy carrier – meaning its environmental sustainability depends on how it is produced.

Almost all hydrogen produced today is "grey," created by pulling hydrogen molecules from fossil fuels like methane (CH_4). Green hydrogen is mainly produced via electrolysis using renewable electricity to split water molecules into hydrogen and oxygen gases.

Currently, grid-connected electrolyzers produce grey hydrogen. Though green hydrogen currently accounts for no more than 4% of total production, volume should increase in the next five to ten years as the cost of electrolyzers and renewable energy decreases.

Green and clean versus grey and dirty



More than 96% of all hydrogen produced is grey – produced using fossil fuels. Green and clean hydrogen created by electrolysis accounts for only around 4%.
Source: Deloitte

[2] Tank to wheel (TTW) efficiency is the ratio of energy output from the wheels and the energy content of the fuel. While diesel fuel is energy dense, a substantial amount of that energy is lost in the combustion process (e.g., heat loss, pump losses, mechanical losses in converting burning fuel to the drivetrain).

Infrastructure

Getting it into the tank

Logistics is another big challenge facing hydrogen. This includes transmission (transport from production center to distribution center) and distribution (transport to fueling stations). Even though a logistics infrastructure to distribute gaseous or liquid hydrogen exists, moving hydrogen is challenging and expensive.

Transmission

There are many ways in which hydrogen can be transmitted and stored before being locally distributed, including tanker ships, pipelines, trucks, and rail.
Shipping entails converting hydrogen to its liquid state, which is very costly due to the extremely low temperatures and large volumes required. In addition, liquid conversion carries costs, both in terms of energy efficiency and economic impact.

Another option is conversion to ammonia, which is much easier to transport and for which a developed logistics network already exists. However, due to energy losses and costs of reconversion, it is not an ideal option for road transportation. Pipelines could carry hydrogen in a gas state. However, extended pipeline distribution of pure hydrogen is still five to ten years away. That leaves liquid truck and/or rail transport as the most feasible short-term options. Liquid transport has already been adopted for grey hydrogen supply in many industrial applications.

A supertanker carrying liquified natural gas. For some transport applications, partial infrastructure already exists.

Source: Getty Images

Local distribution and refueling

For local distribution, trucks seem to be the only valid option, but even this is complicated and costly. Hydrogen as a gas is made up of small molecules, so leakage from tanks is common. Moreover, hydrogen as a liquid is also subject to leakage if extreme sub-zero temperatures are not maintained.

A new refueling network would also need to be constructed. Currently, there are only 400 publicly subsidized refueling stations worldwide, a number which would need to grow dramatically to sustain larger fuel cell vehicle fleets. In Europe alone, 3,700 fueling stations would be needed to service a fleet of just 1.2 million fuel cell EVs (and at a price tag of EUR 8.2 billion). And that represents only 0.4% of all vehicles currently driving on EU roads.

Decentralized (distributed) production of hydrogen could reduce transmission and distribution costs. Instead of producing and transporting it from centralized plants, hydrogen would be produced directly at fueling stations, either via natural gas reforming or small-scale electrolysis (see insert box, Is Hydrogen Sustainable?).[3] This would cut distribution costs but significantly increase production costs, further delaying economies of scale. More research into the trade-offs of decentralized production is required to calculate actual benefits.

[3] Steam methane gas reforming (SMR) is the most common method of producing grey hydrogen. Electrolysis is a clean process of producing hydrogen using electricity and water.

Costs

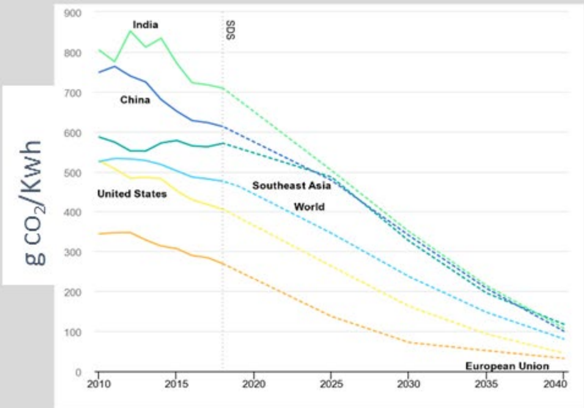
Comparing lifecycle emissions and cost of ownership

Environmental cost – lifecycle emissions

When it comes to tailpipe pollution, fuel cell powered vehicles offer the appeal of zero emission transport. However, one should consider lifecycle greenhouse gas emissions, which in all vehicles are mainly driven by energy sourcing, distribution and manufacturing of components.

Recent studies show that, to reduce lifecycle greenhouse gas emissions to even combustion engine levels, fuel cell vehicles would require very clean electricity (below 200g CO_2eq/KWh) from the electrical grid. This level is about half the current carbon intensity level of the US electricity grid (see Figure 2). In comparison, battery electric vehicles (BEVs) show lower emissions than combustion vehicles (ICE) at current electric grid emission levels of 450g CO_2eq/KWh (see Figure 3).

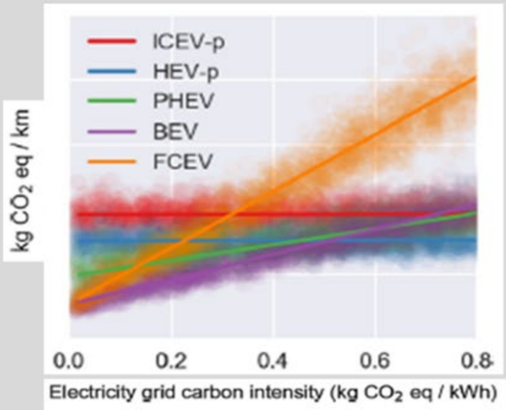
Figure 2 Carbon emissions of electricity grids



The graph illustrates the large differences in carbon emissions of electricity grids in selected countries. It also shows how much they will need to fall by 2040 to meet sustainable development scenarios.

Source: IEA

Figure 3 Fuel cells worse than combustion



The graph shows the lifecycle emissions for medium size passenger vehicles using electricity from grids that vary in carbon intensities. Dirty electricity grids (> 0.3 kg CO_2) make hydrogen fuel cell vehicles more polluting than combustion engines (ICEV-p).

Source: Cox et al., 2020

Economic cost – total cost of ownership

Green hydrogen-powered vehicles have the potential to reduce emissions from transportation, but are they economically competitive? Prices for fuel cell components and hydrogen are the main drivers of total cost of ownership (TCO). Manufacturing fuel cells at-scale would reduce overall costs. Likewise, an increase in the production volume of green hydrogen and a decrease in the cost of renewable energy required for electrolysis would further mitigate TCO. Driven by reductions in renewable energy prices, the price of hydrogen in best-in-class renewable developers could decrease to half of today's average price over the next three years.

Though renewables play a large role in hydrogen pricing, other factors are also at play. Differences in energy prices, manufacturing capabilities, market structures and regulations mean underlying cost drivers will vary considerably by region. For example, the cost of ownership of a hydrogen-powered bus will reach parity with petrol-burning buses in 2023 in Europe but four years later in China. On average, fuel cells should reach cost parity with gas-powered vehicles within the next ten years, with the cost gap decreasing rapidly before the second half of the 2020s.

Use case analysis

Comparing hydrogen vs battery power in practice

Despite significant technical, economical, and logistical challenges, hydrogen appears to have the potential for decarbonizing road transportation. But is it the most efficient pathway for cutting transport emissions? Our analysis implies that the answer is no, at least not for most applications.

BEVs have a significant technological and infrastructural lead over FCEVs that give them distinct advantages in terms of cost-efficiencies, particularly with respect to passenger mobility (public and private) and short-haul freight transport.

Private mobility

The first key advantage of BEV mobility is the greater energy efficiency. Assuming hydrogen is sourced via electrolysis, batteries are twice as efficient as equivalent fuel cells. This means that hydrogen cars require at least twice the amount of renewable electricity to cover the same range.

Another advantage is battery-powered EV's growth in market share which is promoted by lower ownership costs for consumers and by a more pervasive and agile charging infrastructure. Sales of BEVs reached 1.98 million vehicles in 2020, representing almost 2.7% of total new car sales. That share is expected to rise above 55% globally by 2040 driven by EV players such as Tesla, Nio and Xpeng, and incumbent car manufacturers. In contrast, only about 20,000 hydrogen powered cars are currently on the road worldwide.

Increasing market penetration generates lock-in effects, as heavy investments in BEV charging infrastructure from private and public players are already underway. Diversity of models, improving ranges, and, of course, low emissions have made BEVs the popular favorite for replacing combustion engines in passenger mobility. Building additional infrastructure in parallel to support fuel cell electric vehicle uptake and expansion seems unnecessary and wasteful.

In addition, BEVs have the advantage of allowing home charging. This is crucial as it distributes infrastructure costs across a larger group of stakeholders, while helping to stabilize and optimize the electrical grid. Moreover for consumers, home charging carries additional benefits: they can generate their own transport energy from roof-top solar installations and they can save considerable time by eliminating stops at charging stations.

Hydrogen fuel tanks can be re-stocked in minutes.

Source: Getty images

Nevertheless, advocates of hydrogen transportation argue that fuel cells still have clear advantages over battery power in three critical areas. The first is fueling time. Like filling a car with gas, hydrogen-powered cars can fully charge in minutes.[4] The second is range. Hydrogen vehicles on average can travel longer distances on a full fuel tank. However, this is not such a clear advantage, as recent developments in battery capacity have allowed battery electric vehicles to reach ranges of over 600km, significantly narrowing the gap with fuel cells.

The third critical area where fuel cells have an advantage is the costly and carbon intensive process of battery manufacturing. It is estimated that 30-50% of battery-powered vehicle emissions derive from this stage. However, the absolute value could be halved with battery recycling and decarbonization of the electric grid, efforts that many governments are starting to pursue.

Finally, battery manufacturing raises concerns regarding the ethical sourcing of raw materials like cobalt; however, many manufacturers are addressing these concerns and aiming to achieve cobalt-free batteries in the near future.

[4] Charging speeds vary among BEVs. Tesla's supercharging network claims it can charge its vehicles in 15 minutes for 320 km of distance. A standard Tesla wall connector promises 53-71 km of range per hour of charge depending on the model. So

Public transportation

Public transportation represents an interesting use case for hydrogen-powered vehicles and some municipalities have already started pilot projects. In 2019, the city of London announced its intention to roll out 20 buses to cover three urban lines. Infrastructure requirements for public transport are less significant as fixed routes require fewer fueling stations. In addition, the higher usage rate compared to private vehicles would help make the total cost of public transport competitive with gas-powered bus options in a shorter timeframe.

Hydrogen fueled public transport is being tested in London.

Source: Getty images

However, these advantages would also apply to battery-powered EVs and, all else equal, BEVs would still require two to three times less energy than fuel cells vehicles to operate. Furthermore, green hydrogen is still scarce, and substantial amounts of it won't be available until the end of the decade. Even then, supplies won't be enough to match demand.

Critics of battery-powered public transport cite problems that might accompany higher adoption. Overnight charging of entire fleets could over-extend the charging capacities of centralized depots. However, the level of adoption required to cause this problem appears likely only in the long term; by then, investments to boost charging capacity will have certainly been made. Furthermore, the overnight charging requirements could be mitigated by fast charging bursts during operation.

An overhead electrified train. Many countries in the EU have extensive electric public transit networks.

Source: Getty images

For these reasons, we do not believe the additional energy demands from battery-powered electric vehicle fleets justify investments into public fuel cell fleets. In addition, viable electrified public transport (including trains, trams, and buses) has been operating for decades. A more reasonable approach would be to expand these tried-and-tested technologies rather than introduce a completely new, unproven, and expensive hydrogen concept.

Short-haul trucking

The use case of hydrogen-powered short-haul trucks (also referred to as light-duty trucks) shares many similarities with public transport vehicles, and pilot projects are underway to assess their success for delivery service and short distance logistics. One example is provided by the Chinese start-up, STNE, which recently deployed a fleet of 600 vehicles in the Shenzhen area, just north of Hong Kong.

However, given that the typical distance covered during short-haul trips could be easily serviced by existing battery-powered vehicles, the growing interest seems somewhat unwarranted. In addition, total cost of ownership for fuel cells is expected to reach parity with battery and combustion vehicles by the middle of the decade; but beyond that, no significant gains are expected. That means there is no overwhelming cost incentive for switching from batteries to fuel cells. And, as with public transport, the greater efficiency and current range offered by batteries represent significant hurdles to the adoption of fuel cells in short-haul trucking.

Long-haul trucking

Different considerations must be made for the use of fuel cell technology in long-haul trucking. In this use case, many argue that longer ranges, shorter fuel times, and higher payloads make fuel cell trucks superior to battery-powered EVs. In addition, a network of fixed routes would facilitate the development of the required fueling infrastructure. This stronger case is underscored by the fact that Toyota, Hyundai, and Shell have all announced plans to expand into hydrogen-powered long-distance transportation.

American long-haul freight trucks with gas tanks on the side are better suited for carrying hydrogen fuel.

Source: Getty images

However, the latest advancements in battery technology are increasing the attractiveness of battery-powered long-haul trucks. These are expected to reach a range of 800km in the first half of 2020, comparable to the 1000km range of long-haul fuel cell EV trucks that will be commercially available in the second half of the 2020s.

A longer driving range also implies a larger and heavier battery. The estimated battery weight to reach such a range varies from 3,000kg to 5,000kg, depending on the final energy density of the entire battery stack. However, much of this battery weight could be compensated by more flexible battery drivetrain designs. Fuel cell EVs might not offer such flexibility due to the cylindrical shape of hydrogen storage tanks.

Hence, we believe battery-powered trucks are the most attractive option for decarbonizing long-haul trucking in markets such as Europe, where trips of less than 800km constitute 78% of all trucking activity. Moreover, regulations that impose driver breaks make longer trips more expensive, such that freight trains provide more efficient and economical solutions.

The picture is different in markets like the US where the rail infrastructure is less extensive and less electrified, and where securing financing for major investments poses challenges.[5] In addition, long-distance trips are more common (in 2018, up to 37% of all trucking activity) and the American design of heavy-duty trucks, with tanks mounted on the sides of the vehicle, could provide a solution to the large storage volumes required for hydrogen transport. Furthermore, the low price of renewable energy in the continental US could make green hydrogen-fueled trucks economically competitive in the short term.

For these reasons, we acknowledge that fuel cell electric vehicles could be a feasible short-term option to decarbonize the long-haul trucking sector in the US. A better long-term investment, on the other hand, would be to improve, expand and electrify the underdeveloped rail infrastructure.

Forklifts

Forklifts represent an interesting use case for fuel cell technology adoption. Here, fuel cells have a clear advantage over battery-powered forklifts as they can be operated for longer stretches without stopping mid-shift for a lengthy recharge period that takes both forklift and driver out of action. It takes fuel cell forklifts around three minutes to refuel, allowing business continuity and greater efficiency. As a result, labor costs related to refueling can be reduced by up to 80%.

Forklift fuel cells are cost-competitive in warehousing and logistics.

Source: Pexels

Given the growth surges in sectors like e-commerce and construction that rely on highly efficient inventory management and distribution operations, fuel cell forklifts can make sizable contributions. Amazon and Walmart are increasing them in warehousing facilities; Walmart alone is now operating approximately 10,000 fuel cell forklifts in the US. Still, installing a hydrogen fueling infrastructure presents a challenge. Set-up costs hamper the economic competitiveness of fuel cell solutions and might limit their adoption to large sites with a high number of forklifts in operation.

[5] U.S. railway services are almost entirely privately owned and managed, as opposed to their government-controlled European counterparts.

Due to significant operational efficiencies, we believe that fuel cell technology offers the most viable option to decarbonize the remaining non-electrified share of the sector, at least for larger operations. In cases where smaller forklift fleets are required, we believe that the high set-up costs of the fueling infrastructure make battery-powered forklifts the preferable option.

Conclusion

So, is the hype around hydrogen justified? Our answer is, yes, but the hype should be directed to the right sectors. Within transportation – particularly private mobility, public transport and short-haul trucking – battery or overhead electric vehicles are environmentally and economically better options. Moreover, for long-haul trucking, battery-powered electric vehicles are more efficient and viable solutions in markets like Europe where short-haul represents the bulk of all freight trips. However, in the US, where long trips are more frequent, the outlook for hydrogen fuel cells is more favorable.

Forklifts are the one area where fuel cells have the clearest economic and technological advantage over existing alternatives; but even here, fuel cell forklifts' advantages may be limited to large-scale warehousing and construction.

Hydrogen may not be the immediate solution for pollution in transportation, but its future is still bright. Green hydrogen will provide the critical link for carrying and storing renewable energy for use in heavy-emission sectors where electrification via the power grid is infeasible. Many of these industries are already using grey hydrogen, so adoption costs for switching to green would be minimal. In the decades ahead, as technological barriers fall and production ramps up, green hydrogen will eventually become a mission critical resource for controlling pollution.

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