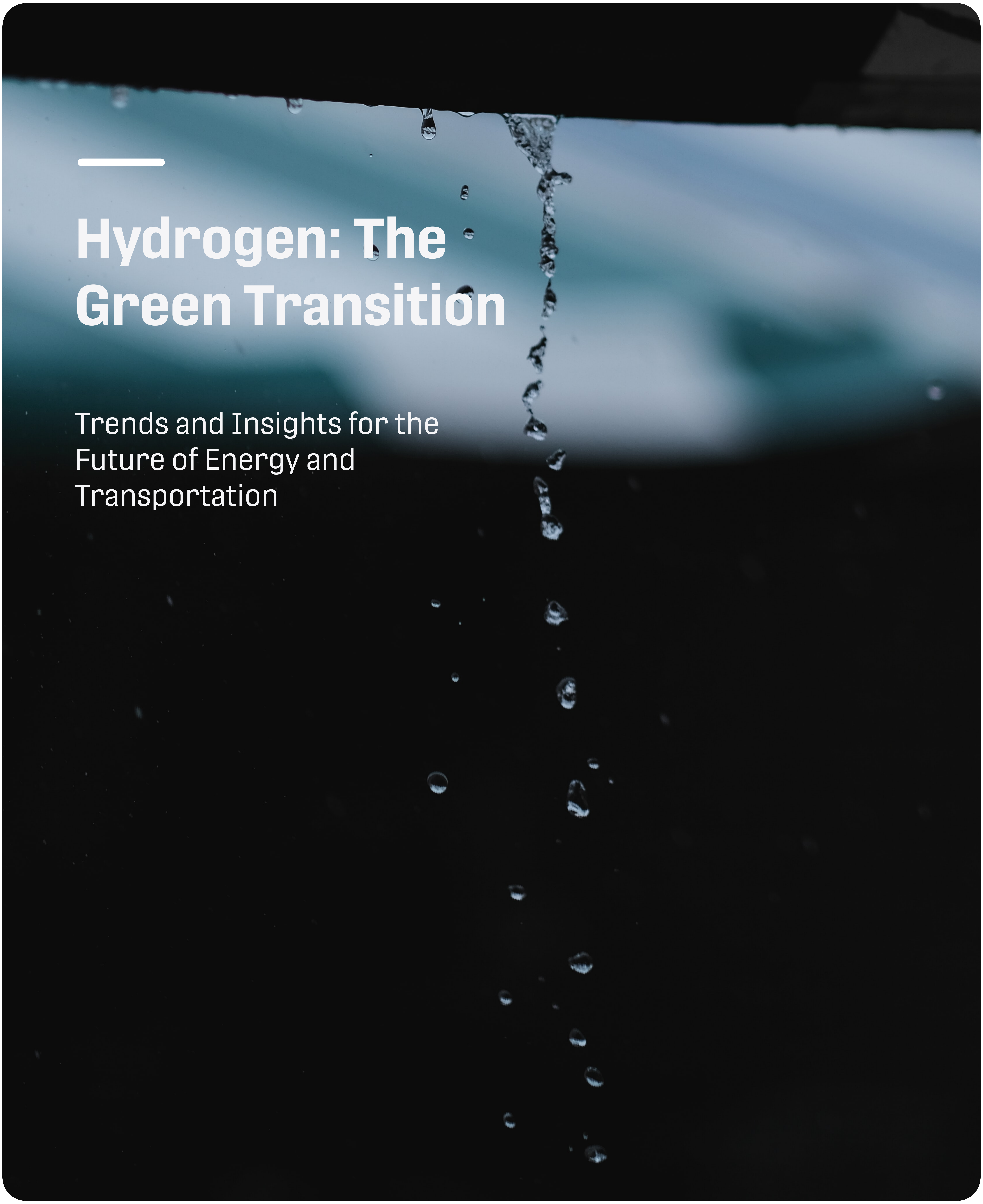

Hydrogen: The Green Transition

Trends and Insights for the Future of Energy and Transportation

PLUG AND PLAY ENERGY

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Introduction

The use of hydrogen in our energy landscape has a storied history dating back to even the first internal combustion engines which originally used H2 for fuel. It is the first and lightest element on the periodic table, and stands unrivaled as the most abundant chemical substance in the universe. It is also known for its incredible storage capabilities, as it has the highest energy per mass of any other fuel. Yet, despite how well known its general properties are, we are only at the infancy stages of harnessing its full potential. Unlike other fuel sources, Hydrogen is inherently clean, producing only water when consumed in a fuel cell. Furthermore, avenues to produce hydrogen have been developed utilizing a vast array of feedstocks and inputs, including natural gas, biomass, nuclear power, and even renewables.

For these reasons, coupled with recent engineering and infrastructural advancements, hydrogen is riding a surge of popularity throughout the energy and mobility industries. Governments around the world continue to set incentives and targets for continued hydrogen production and implementation. Even here at Plug and Play we can't attend more than a few meetings without hearing a colleague or partner mention their interest, or ask what the latest developments are. For this reason we'd like to take you on a deep dive into the various market parameters, trends, and insights that we've formulated, and we hope you'll come out with a broader appreciation for hydrogen as a fuel source, tempered only by the necessary challenges that lay ahead.

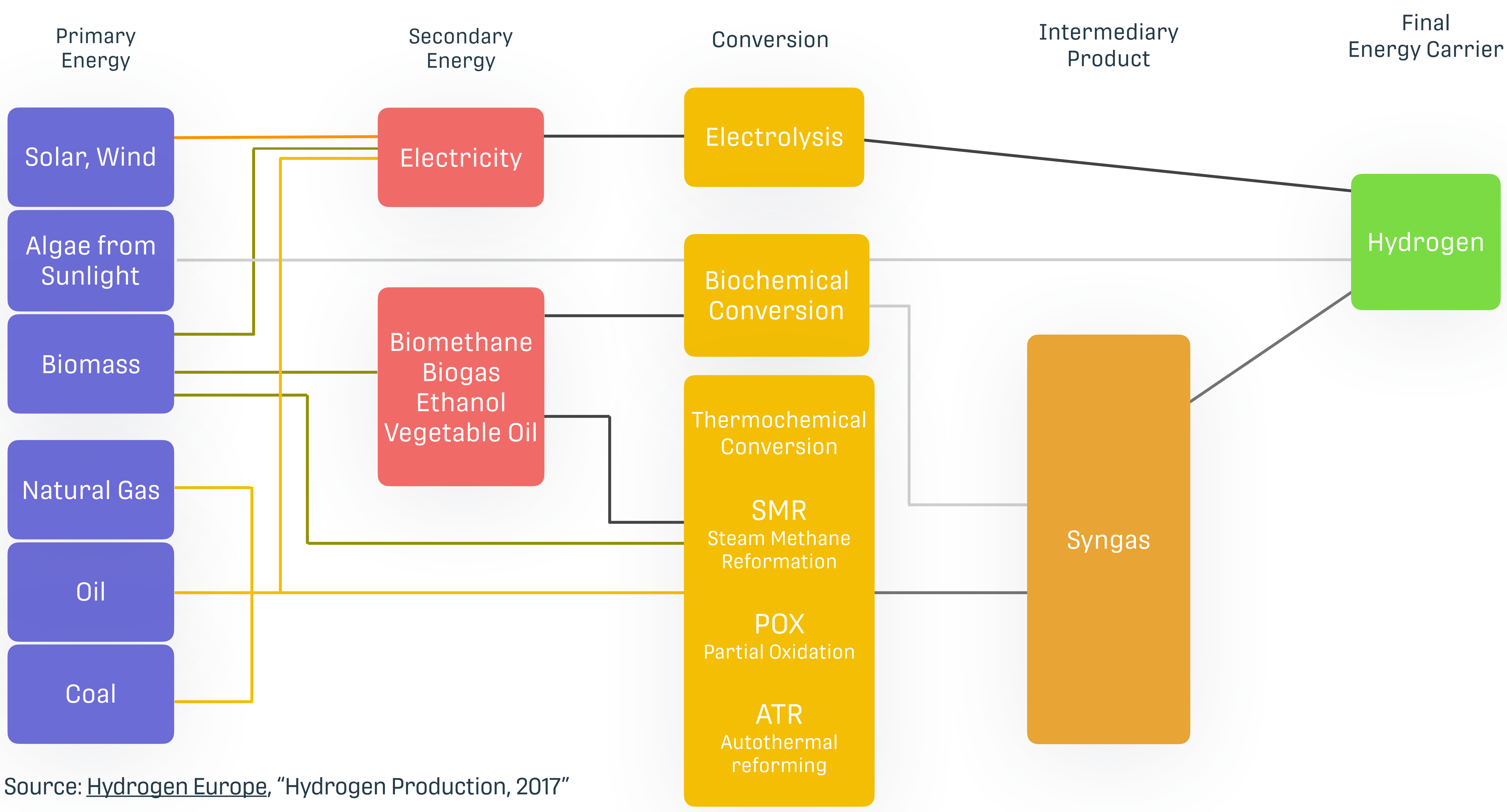
How Hydrogen is Produced Today

Hydrogen is produced in a wide variety of processes from renewable and non-renewable sources each associated with differing carbon intensities. Hydrogen rarely exists in nature in its elemental form and thus must be separated out from other compounds. It is an incredibly versatile energy carrier that can provide long-term energy storage at scale. There are many ways to produce hydrogen; however, only two options are significant in the United States: steam-methane reforming and electrolysis.

Steam-methane Reforming (SMR) is the most common hydrogen production method used in the United States today. Steam methane reformation is a process which utilizes high temperature steam (700°C–1,000°C) to produce hydrogen from a methane source, such as natural gas. Methane reacts with high temperature steam at high pressure in the presence of a catalyst to yield hydrogen, carbon monoxide, and carbon dioxide. This method is largely used by commercial hydrogen producers and petroleum refineries globally.

Electrolysis, or "power-to-gas," is the process in which an electric current splits water into its elemental components, H2 (hydrogen) and O2 (oxygen). And finally, there are many other methods being studied today to manage peaks associated with the different renewable energy resources being added to the grid such as microbes that use light to make hydrogen and converting biomass into gas or liquids to separate out hydrogen.

Production Methods



Source: Hydrogen Europe, "Hydrogen Production, 2017"

Types of Hydrogen

Hydrogen is defined by the original feedstock used to produce hydrogen and the subsequent carbon footprint associated with production.

Grey Hydrogen

Grey hydrogen is produced from natural gas through SMR. Grey hydrogen has the largest carbon intensity of the three and is the cheapest to produce, ranging between $0.91/kg - $1.42/kg. The price is largely driven by the cost of natural gas as well as the price CO2 is trading on carbon markets. It is estimated that over the next decade as these costs go up the price of grey hydrogen will reach $2.00/kg.

Grey hydrogen makes up 99% of global hydrogen production, 10 million tons of the hydrogen produced in the US today comes from converting methane gas using SMR and releases large amounts of carbon dioxide into the atmosphere.

Blue Hydrogen

Blue hydrogen is the next color on the hydrogen color wheel accounting for less than 1% of the remaining hydrogen produced. Blue hydrogen is made in the same way as grey hydrogen, but captures, stores, or reuses 80-90% of carbon emissions that are produced. The cost of blue hydrogen lies between $1.34/kg - $1.85/kg depending on the price of natural gas and technologies used for carbon capture utilization and storage.

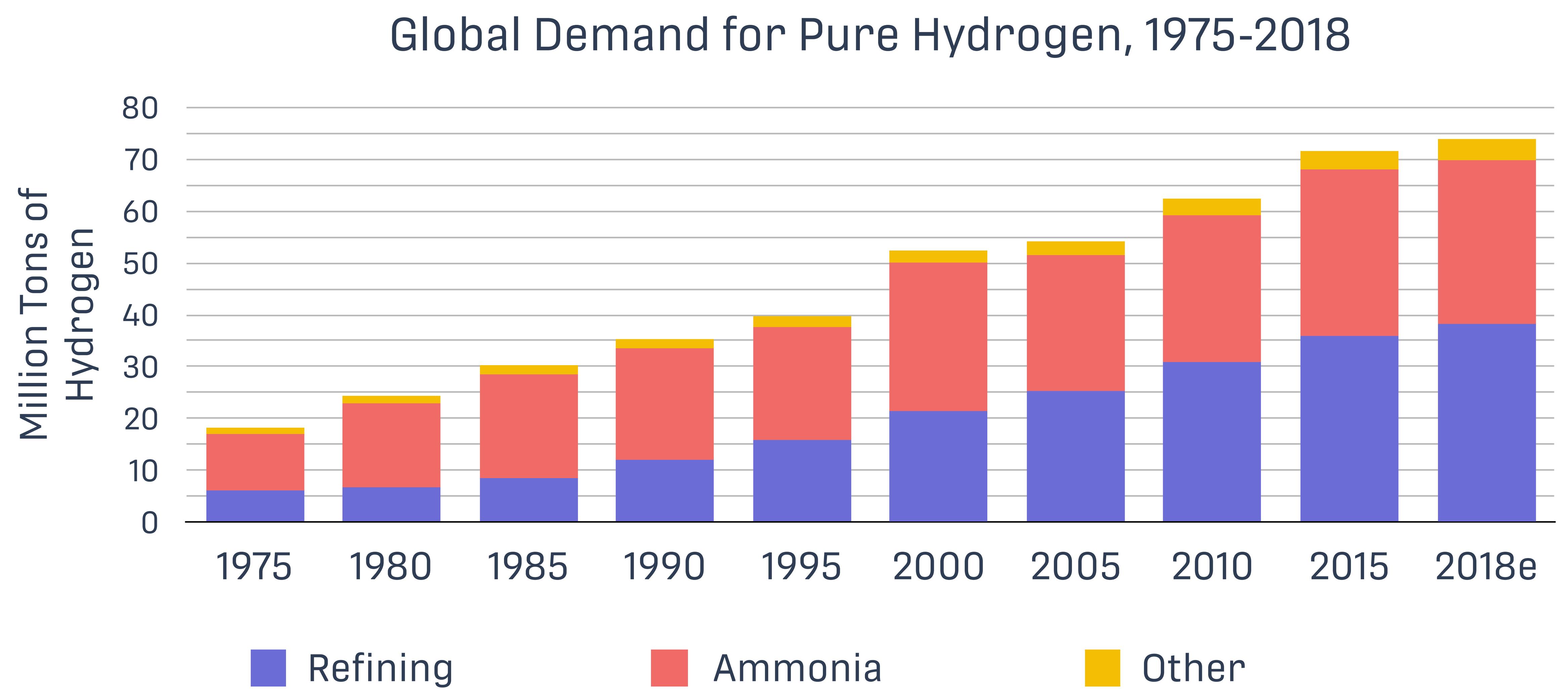
Current prices of carbon capture utilization and storage (CCUS) stand at $50-$70/ton of CO2, however, as corporations scale up production the subsequent cost of production will be driven down as the manufacturing methods are standardized. CCS has received billions of dollars in funding, and is the most costly technology in the scale up process. CCS requires facilities to be built to bury CO2 deep in the ground to ensure it never reaches the atmosphere. However, the timeline for most of these projects is 6-10 years and is expected to capture less than 60% of the emissions produced, which does not include the greenhouse gas emissions produced in the production and transportation of fossil fuels.

Green Hydrogen

Green hydrogen is produced by running an electric current through water using renewable resources, such as solar or wind power, to produce zero-carbon electricity in a process known as electrolysis. In the US where the cost of energy is low, green hydrogen costs three times the price of natural gas , between $3.10/kg - $5.00/kg, due to the costs associated with electrolysis. It is predicted that these costs will be brought down by over 70%, as government incentives and large corporations invest in clean energy and drive costly inefficiencies out of the process particularly as countries across Europe, Australia, and Singapore spearhead these efforts.

Green hydrogen has the power to decentralize the energy industry, relying solely on renewables and putting power in the hands of the consumer. With high levels of renewables continually being added to the grid a green hydrogen future is becoming a reality. In many areas around the world, such as the Middle East, North Africa, and Latin America, where the cost of green electricity has reached $0.02/kWh this is already happening. In the US green hydrogen needs to reach $1.50/kg in order to drive adoption in domestic and export markets, which some groups have predicted to happen over the coming decade.

Industry Demand for Hydrogen



Source: IEA Hydrogen Report, "Global Demand for Pure Hydrogen," 2019.

The demand for hydrogen has grown steadily since the mid 1970's. This steady increase can be attributed to the element's ability to provide seasonal storage capacity, having the ability to charge consecutively over weeks without discharging. Hydrogen can be used in the production of fuels such as synthetic gas, ammonia and substances made by synthesizing different gases. Based on the Baker McKenzie report Shaping Tomorrow's Global Hydrogen the top 4 industrial uses are oil refining (33%), ammonia production (27%), methanol production (11%), and steel from the reduction of ore (3%). The hydrogen produced today originates from the use of fossil fuels, without utilizing either carbon capture utilization or storage; this grey hydrogen makes up 6% of the world's total energy demand.

There are many factors hindering the growth of hydrogen worldwide, the largest of which is the cost of fuel. Fuel makes up 45-75% of the total cost in the hydrogen production process. Low gas prices in the Middle East, Russia, and North America give rise to some of the lowest hydrogen production costs. Conversely gas importers such as Japan, Korea, China, and India have to contend with higher gas import prices and hence higher costs of hydrogen production. As the industrial demand for hydrogen escalates and the cost of fuel decreases the market is predicted to surpass $25 billion by 2030 and jump to nearly $2.5 trillion by 2050. The lack of progress on government mandates, incentive programs, and accurate corporate reporting all prevent further adoption of blue hydrogen, despite its use as a low carbon production method. Once policy regulations and mandates are universally established corporations will be forced to use lower emission energy production methods.

Future Applications

Hydrogen has the potential to disrupt every industry by replacing fossil fuels in all major industrial applications from buildings and air and land transportation to steel production and beyond.

Road transportation has been a notoriously difficult industry to decarbonize over the years. Fuel cells which use hydrogen as a fuel produce zero harmful emissions, have higher energy storage capabilities, have shorter refueling times, and weigh less than batteries. Though an exciting prospect, hydrogen fuel cells are not the only option for emission free transportation in personal car use. Other contenders include batteries and advanced biofuels, and the true winner will depend on the most cost competitive option. However, hydrogen fuel cells are a promising alternative for heavy duty vehicles that cannot rely on electric batteries to carry heavy loads over long routes. Heavy duty freight includes maritime, air, and mass transit. These industries are putting hydrogen at the forefront in the competition for the renewable fuel source of the future. The primary reasons hydrogen has been widely adopted in these industries are the limited changes necessary to existing infrastructure and the environmental benefits seen in industry today.

Buildings make up one third of the world's energy demand, accounting for 76% of electricity use and 40% of all US primary energy use and associated GHG emissions. The opportunities to decarbonize buildings are endless, which not only reduce inefficiencies in energy usage but also reduce costs for building owners and tenants. A process being widely adopted by building owners and operators today is to blend hydrogen into the existing natural gas networks to complement the use of heat pumps and quickly lower their carbon intensity. By blending hydrogen with natural gas, commercial and residential consumers can power existing appliances, generate electricity, and produce the necessary heat and power for heating systems. Other energy intensive industries such as steel, aluminum, cement and even refineries, which are huge carbon emitters, can use hydrogen as a feedstock for many chemical processes. Since hydrogen is capable of achieving the high temperatures necessary for melting, gasifying, drying, catalyzing etc. the opportunities for financial gain by transitioning to a clean energy future for industrial suppliers are quite extensive.

Lastly, power generation, balancing, and storage offer various pathways for hydrogen and hydrogen-based fuels. Hydrogen is typically consumed at site once it is produced, most notably in the production of ammonia which is synthesized when hydrogen is co-fired in coal power plants. Hydrogen can be stored for later use as a liquid or a gas; this process typically requires high pressure and cryogenic temperatures. Hydrogen is a highly volatile gas and must be either adsorbed onto the surface of solids or absorbed within solids to allow for long duration storage or use in transportation. Hydrogen can be stored in its gaseous forms underground in salt caverns, which is a common method of fuel storage that has grown in popularity as hydrogen's role in decarbonization becomes clearer. Another appealing use case for hydrogen storage is managing seasonal storage of renewable resources during peak times.

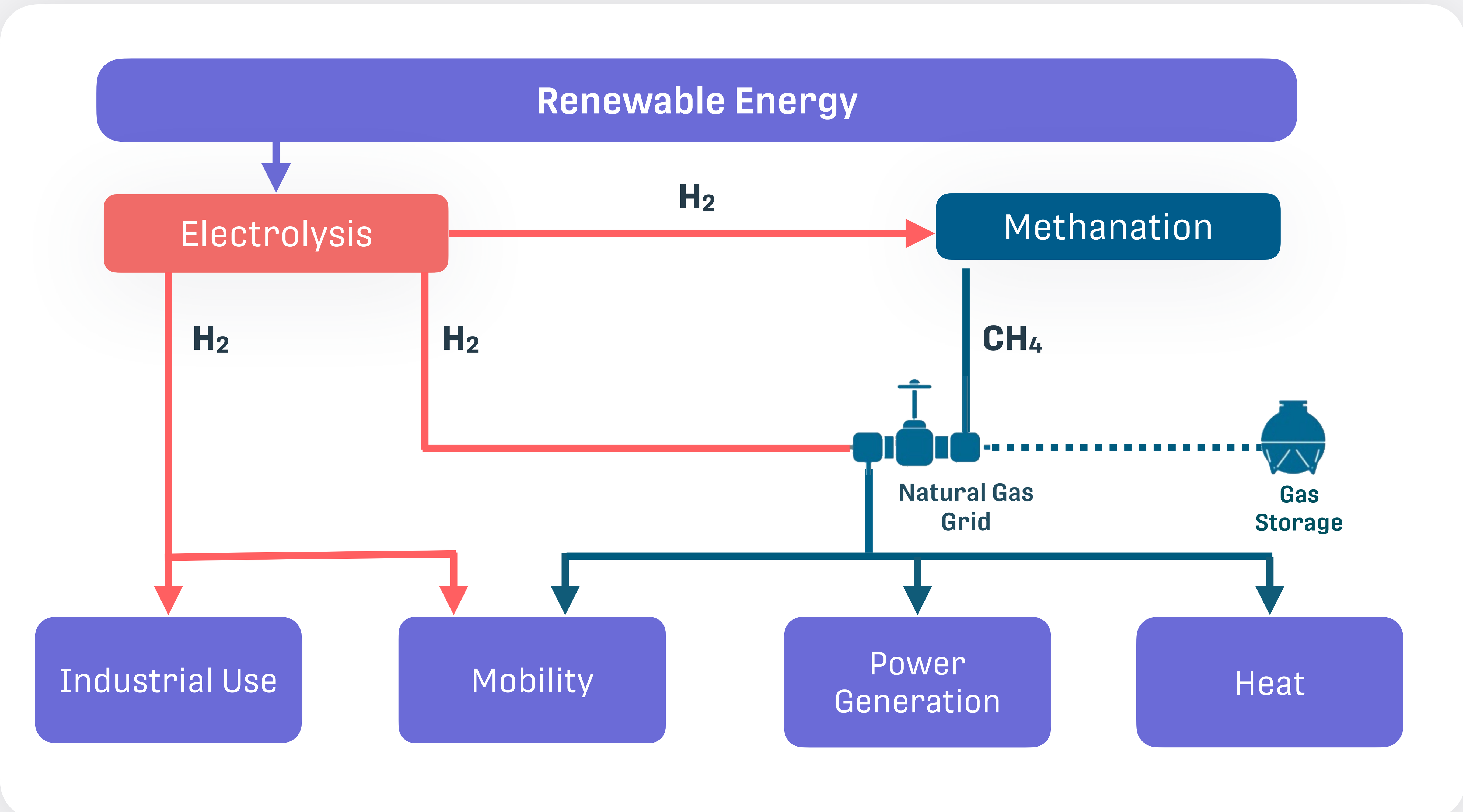
The path forward for hydrogen ultimately depends on early adopters. This is truly a chicken or egg situation. The cost of hydrogen production can only be brought down as production is scaled up, and for this to happen capital needs to be invested. Only then will hydrogen be seen as a profitable long term clean energy solution.

Power-to-Gas (P2G)

Power-to-gas converts electricity into a gaseous fuel such as hydrogen or methane. Most P2G systems use either electrolysis to produce hydrogen directly or a two-step P2G process which converts hydrogen into syngas, methane, or liquified petroleum gas.
There are two main methods to produce hydrogen: electrolysis or methanation. Electrolysis works by using electricity (power) to reduce water into gas (hydrogen and oxygen) while methanation combines hydrogen and CO2 to produce methane and water. Methanation, both steam and biological methanation, is primarily used to purify synthetic gas, manufacture methane, and/or produce ammonia in large plants. These gasses are generally used as chemical feedstocks or converted back into electricity using conventional generators, such as gas turbines.

Power-to-gas allows energy from electricity to be stored and transported in the form of compressed gas using existing infrastructure. This is vital for hydrogen to act as a leading fuel source. P2G is often considered the most promising technology for seasonal renewable energy storage and is propelled by government incentives and regulatory policies demanding the reduction of corporate carbon emissions. For example, in Germany, a country wide goal to bring down greenhouse gas emissions by 95% by 2050 is forcing natural gas suppliers to replace carbon emitting fuel sources with synthetic gas to avoid damaging emissions during the combustion process.

Another main driver in the power-to-gas movement is the ability for renewable power to be transported to areas of high demand, which were previously non-transportable. The path towards profitability is still long, however, as more companies adopt the new technology and prove the financial benefits as well as environmental advantages derived by switching to P2G systems the market is slated for success.



Source: "Introduction to 'Power to Gas'" by Energy Storage For the Grid & Transportation, LAS 493 Special Topics in Energy and Sustainability, published in 2017.

Startup Highlights

Founded in 2017
San Francisco, CA.
Energy Batch 7 cohort

Charm is developing biomass gasification systems to produce carbon-negative hydrogen. Unlike prior biomass gasification which focused on electricity generation or liquid fuels like ethanol and methanol, Charm is focused on biomass conversion to hydrogen.

Primary markets are transportation fuel cells (cars, forklifts, heavy duty fleets), refineries (starting in California with the Low Carbon Fuel Standard), and ammonia production. Charm has raised Series A funding from undisclosed investors.

Founded in 2019
Singapore
Energy Batch 7 cohort

$110B of hydrogen is used every year in refineries, fertilizers and chemical plants. About 15% or $16 billion of it is burnt or released because it is deemed "too difficult to recover". On top of this, it takes about 100 million tons of CO2 to generate that hydrogen in the first place.

DiviGas, part of Plug and Play's Silicon Valley Energy Batch 7 cohort, has invented a new type of membrane, which is a filter at the molecular size to tackle just that. It can separate, recycle, and reuse that previously 'lost' hydrogen, as well as reduce the need for more carbon dioxide, saving millions of dollars and millions of tons of CO2.

Founded in 2018
Santa Barbara, CA.

C-Zero is developing a process for removing the carbon found in natural gas, which will allow its customers to enjoy low-cost, on-demand energy without producing CO2.

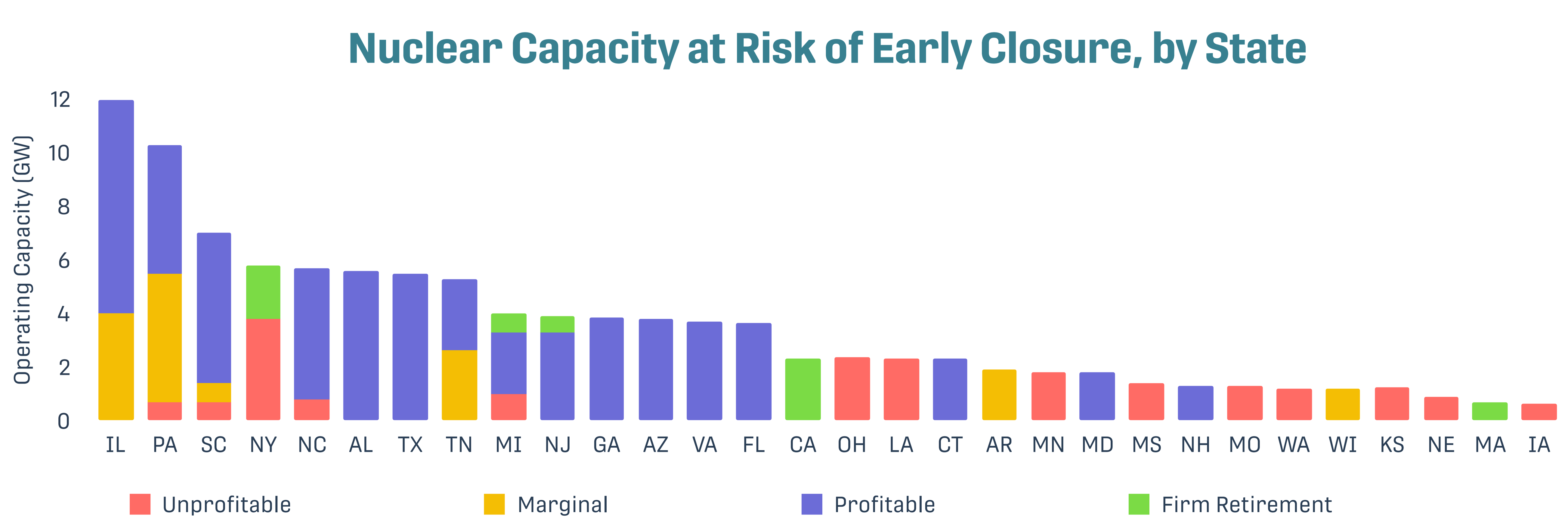
The company's proprietary process utilizes high temperature liquid catalyst systems to crack methane, the primary molecule in natural gas, into hydrogen and solid carbon. The solid carbon can be permanently sequestered, while the hydrogen can be sold as an industrial commodity or used to produce electricity and heat. When renewable natural gas is used, the company's technology is carbon negative.

Nuclear Power and Hydrogen

Nuclear power plants are thermal power stations that generate electrical energy from heat. They were deemed a beacon of hope for a low carbon future in the 1990's and make up 20% of America's power. However, as renewables begin to surpass traditional energy supplies many nuclear plants have prematurely shut down, been relatively abandoned, or are en route to retirement. The chart below showcases the operating nuclear capacity of power plants throughout the 50 states.

Over 180 commercial, experimental or prototype reactors have shut down, and over 500 research reactors have been put out of production due to a lack of market value and the continued record low prices of natural gas. Most nuclear plants are looking at bleak futures and are fishing for solutions to keep their reactors in business. One promising solution is hydrogen.

Nuclear power plants already possess the critical infrastructure necessary to produce hydrogen. This includes high quality steam for steam methane reformation and electrolysis. They are also ideal for low-temperature electrolysis methods which take advantage of low electricity prices during the plants' off-peak hours to produce hydrogen. A slowdown in electricity demand in tandem with competing low natural gas prices in North America have driven most plants out of business. Many have struggled to maintain profitability as intermittent power sources are added to the grid forcing operators to shut down production during peak hours at a huge expense to the industry. Across the US and around the world government entities are supporting projects to prove economic gains for corporations that produce and sell hydrogen regionally as a commodity and to reach agreed climate goals.



Source: Union of Concerned Scientists, "The Nuclear Power Dilemma"

Electricity from Hydrogen: Fuel Cells

From fuel cell applications in new FCVs (fuel-cell vehicles) to other methods of transportation in areas including the maritime space, the applications of hydrogen in reference to electricity and power generation are numerous.

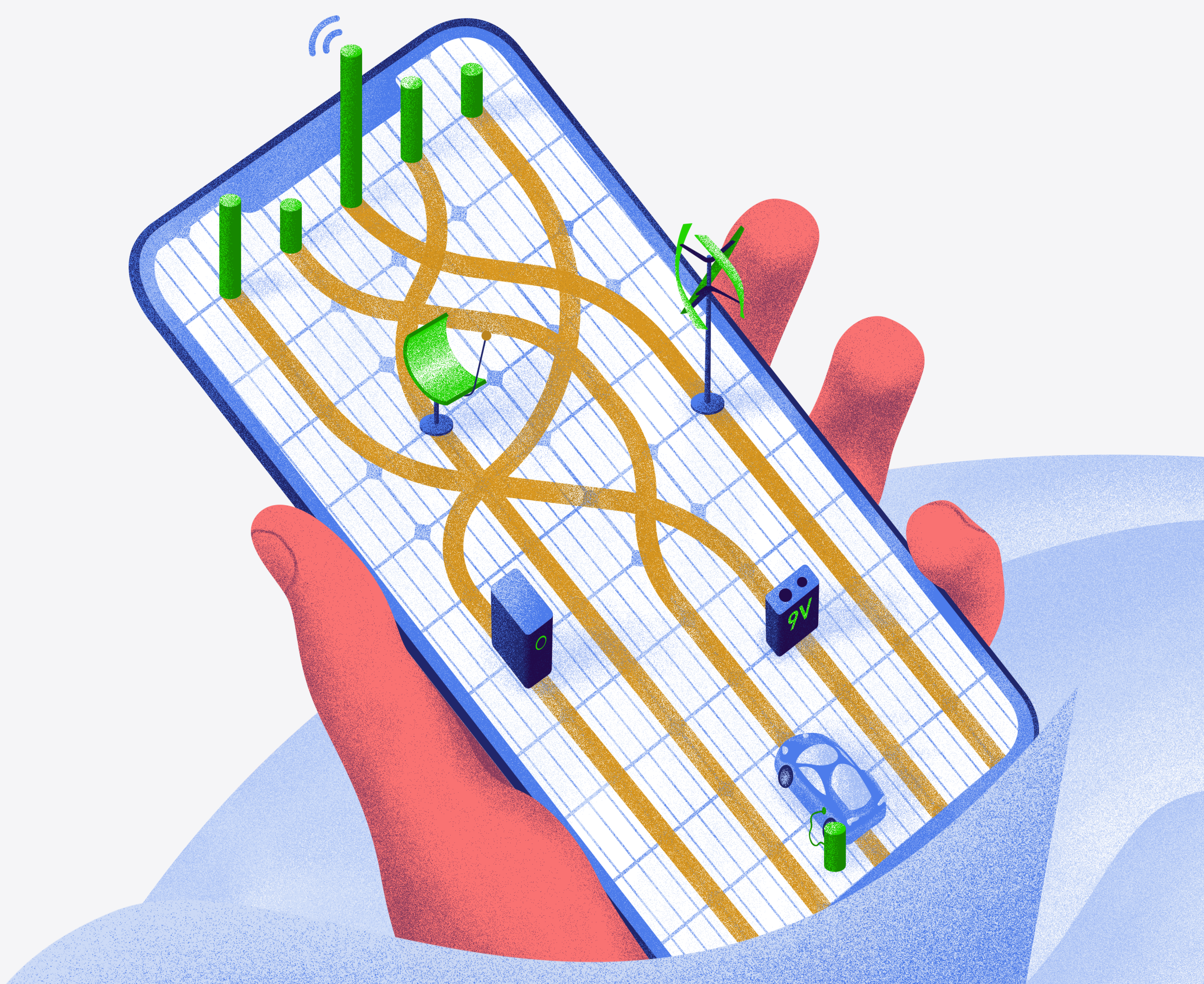
Hydrogen's high energy density allows it to be used for many diverse applications within energy generation. The most popular of these include pure and clean electricity generation via fuel cells, implementations and integrations in transportation via the aforementioned FCVs, and direct integration with industrial supply chains by leveraging the power of waste heat and other remaining power sources.

Hydrogen is a clean and versatile fuel, and when used to generate clean electricity it can reduce CO2 emissions by around 90%. According to the Department of Energy, cost, performance, and durability are still key challenges in the fuel cell industry.

Cost challenges mainly rely on some of fuel cells' key components, with platinum still representing a major barrier towards large scale fuel cell adoption. On the performance front, degradation and life cycle evaluation are still some areas where improvement can be achieved.

The big question mark for massive fuel cell deployment is whether they can function and achieve notable durability under changing functioning conditions.

Technologies achieving significant breakthroughs in any of these three barriers could unlock the next stage for fuel cell adoption. On the following page are some of the startups helping to take fuel cell development to the next level.



Startup Highlights

CELCIBUS

Founded in 2019
Goteborg, Sweden

Celcibus catalyzes the transition to renewable energy through providing less expensive and more sustainable fuel cell components. Celcibus has developed a novel platinum-free catalyst for fuel cells and verified its function in a PowerCell model S2 fuel cell stack. With the new catalyst, Celcibus can lower the manufacturing cost, eliminate the need for noble metals, and greatly simplify the recycling process for fuel cells.

PowerUP ENERGY TECHNOLOGIES

Founded in 2016
Berkeley, California, USA

PowerUp Energy Technologies aims to solve the problem of reliability and durability by improving power backup in adjacent sectors to mobility like the maritime industry. PowerUp solves the problem of providing clean energy with portability by delivering a fuel cell backup generator solution. Their customers include the maritime and automotive fleet industries, who desire portable power packs without the need to rely on heavy automotive batteries or the grid.

BRAMBLE ENERGY

Founded in 2016
London, UK

Bramble Energy is a technology company that designs and manufactures a high-performance, low-cost, fuel cell stack. Bramble Energy specifically uses a printed circuit board (PCB) technology to form the structural parts of the fuel cell. The hydrogen fueled PCBFC™ combines a number of patent protected innovative features including a unique lightweight PCB construction, optimized internal flow field design, and an advanced electrode anti-corrosion passivation layer.

Ground Storage and Green Electrolysis

Hydrogen can be stored not only in tanks but also in salt caverns. **When it comes to the industrial storage of hydrogen, salt caverns, exhausted oil and gas fields, or aquifers can be used as underground stores**. Although more expensive, cavern storage facilities are most suitable for hydrogen storage.

When looking at hydrogen production via electrolysis, there are two main methods in the market. The first one is through traditional alkaline systems and the second is with PEM systems.

TRADITIONAL ALKALINE SYSTEMS

- Normally can't operate at pressure.
- Don't usually produce high purity hydrogen, so they need a complicated balance of plants (BOP) for the purification and compression steps later on.
- One of the few exceptions are nickel-based systems, with a notably higher price, but offering a higher gas purity due to a lower gas diffusivity in the alkaline electrolyte.

POLYMER-ELECTROLYTE MEMBRANE (PEM) SYSTEMS

- Also known as proton-exchange membrane systems.
- Produce high purity hydrogen directly from the stack and have a very fast operation.
- Operate in an acidic environment so they rely on very expensive materials like iridium, platinum or titanium.

At the intersection of these methods come innovative startups shown on the following page.

Startup Highlights

Enapter

Founded in 2014
Pisa, Italy
Energy Batch 6 Cohort

Enapter is part of Plug and Play's Silicon Valley Energy Batch 6 cohort. Enapter is on a mission to replace fossil fuels with affordable green hydrogen using their modular anion exchange membrane (AEM) electrolyzer technology, which is scalable across power, industrial, heating, and transport applications. Enapter uses its 'secret sauce' to go to a price point others cannot through its Anion Exchange Membrane (AEM) technology. With the AEM technology, essentially the cells set up similarly with a PEM. This provides the advantages of PEMs in terms of purity and high quality, but with low-cost materials of the alkaline systems. This allows Enapter to make a low-cost stack, with a bill of low-cost materials and a very simple balance of plants.

Case studies:

- Using hydrogen for peak-shaving in France: excess solar used to produce hydrogen for office space.
- First hydrogen project for residential heating: collaborating with a Dutch gas operator and DNV GL to provide hydrogen electrolyzers.

PULSENICS

Founded in 2016
London, UK

Pulsenics develops advanced characterization and analytics tools for the optimization of electrochemical systems running high currents. Specifically, Pulsenics has invented the world's first-of-its-kind hardware that unlocks previously inaccessible key health parameters from the heart of running industrial processes- including those of hydrogen generation.

Traditionally, hydrogen electrolysis systems produce hydrogen through a system that generates hydrogen and oxygen at similar moments during the electrochemical reaction. Huge savings and efficiency could be achieved if this process can be separated at different times. One startup that could potentially help with this is H2Pro.

Founded in 2019
Tel Aviv, Israel

Israeli-based H2Pro is developing an innovative green hydrogen production technology based on a disruptive process called E-TAC (Electrochemical-Thermally Activated Chemical) water splitting. Like electrolysis, E-TAC uses electricity to split water; however, it decouples hydrogen and oxygen production, achieving unprecedented efficiency (95%). As oxygen and hydrogen are not generated at the same time, no membrane is required, making the process inherently safer and simplifying construction and scale-up. Moreover, hydrogen can be produced at high pressure.

Don't forget-

While green hydrogen seems like the obvious gateway to renewable integration, other closely related "cousins" like green methane and green ammonia should not be overlooked.

Green methane is made out of a process called artificial photosynthesis — which could make natural-gas-powered devices carbon neutral. Scientists are using artificial photosynthesis to make methane out of carbon dioxide, water, and sunlight.

One way of making green ammonia is by using hydrogen from water electrolysis and nitrogen separated from the air. Ammonia is much easier to transport and has significantly more energy density but comes with some cons as well, such as its toxicity and its risks when mismanaged in industrial or workplace applications.

Hydrogen Energy Management Systems

As hydrogen production grows into a larger industry, the ability to allow it to be effectively intertwined with renewables to provide seasonal energy storage will present a key milestone in the mass adoption of the technology, aside from helping it reach cost parity. Many startups are innovating around hydrogen energy management systems which involves intelligent electricity generation through fuel cells, hydrogen generation through electrolysis, and all the middle plays involved with managing these complex systems via software.

The Trendsetters: Toshiba's First EMS (Energy Management System)

Toshiba was actually the first developer of H2 EMS solutions back in 2015 at commercial scale. Toshiba first developed this system for Tohoku Electric Power, but there are still massive opportunities to be explored in this space. This system allows utilities to maximize the use of power generation capacity and helps them enable more efficient hydrogen generation via electrolysis and smarter electricity production via fuel cells. As hydrogen increases in percentage of overall capacity, new technologies will be needed to manage its integration into the grid.

Startup activities still remain low in this area of study, with a few companies offering new business model innovations around Hydrogen on Demand.

Startup Highlight

STOREH ENERGY STORAGE TECHNOLOGIES

Founded in 2019
Rovereto, Italy

StoreH has developed an innovative system for energy storage and Hydrogen-On-Demand production. A low cost, scalable, safe and sustainable solution which allows long term energy storage for domestic, industrial and grid stability applications, enabling seasonal storage and 100% renewable grids.

Hydrogen Transmission and Distribution

Regardless of the method of generation, once hydrogen is produced there remains the issue of moving and feeding it out to its final destinations. As if the technical complexities involved with production weren't enough, a whole realm of optimization and business complexity comes into play when considering transmission and distribution. The existence of centralized, decentralized, and middle-of-the-road hydrogen creation necessitates different corresponding methods of transport. Everything from pipelines to tube-trailers are in active use today.

These varying methods for transmission and distribution are currently mixed and matched, taking into consideration different parameters like distance, end-use (which dictates the form in which hydrogen is transported) and cost and commercialization opportunities. The latter are some of the main challenges towards a wider adoption as shown in the figure below.

Cost and Commercialization are the Biggest Challenges for Distribution

Delivery option	Costs [USD/MWh/ 600km]	Technology maturity	Notes
Retrofitting existing gas infrastructure	4,4	Pilot-tested	Calculated based on literature
New hydrogen pipelines	5,5	Commercial	Calculated based on literature
Liquid organic hydrogen carriers (LOHC) per pipeline	22,5	Pilot-tested	Not yet commercial
Liquified transport per truck, train, and ship	68.8 - 73.5	Commercial with trucks, trains; ship-bound under development	Not deemed a promising option
Compressed gas containers per truck	Not considered	Commercial	Not suitable for large-scale transport
Hydrogen blending with methane per pipeline	Low cost at <10% blends, at higher blends costs	Pilot-tested	Assumed only to play a role up to 2030
Metal Hydrides per truck or train	Unknown at industrial scale	Under development	Commercially available for small quantities

Source: Navigant report "Gas for Climate. The optimal role for gas in a net zero emissions energy system", page 86

Transport methods are well developed technologically; the issue relies in the form of hydrogen transportation given its further applications and ways to ensure that distribution channels are always profitable.

In terms of distribution and transmission, the main methods used today are:

Pipelines

Pipelines are likely to be the most cost-effective long-term choice for local hydrogen distribution if there is sufficiently large, sustained, and localized hydrogen. However, distribution today usually relies on trucks carrying hydrogen either as a gas or as a liquid, and this is likely to remain the main distribution mechanism over the next decade.

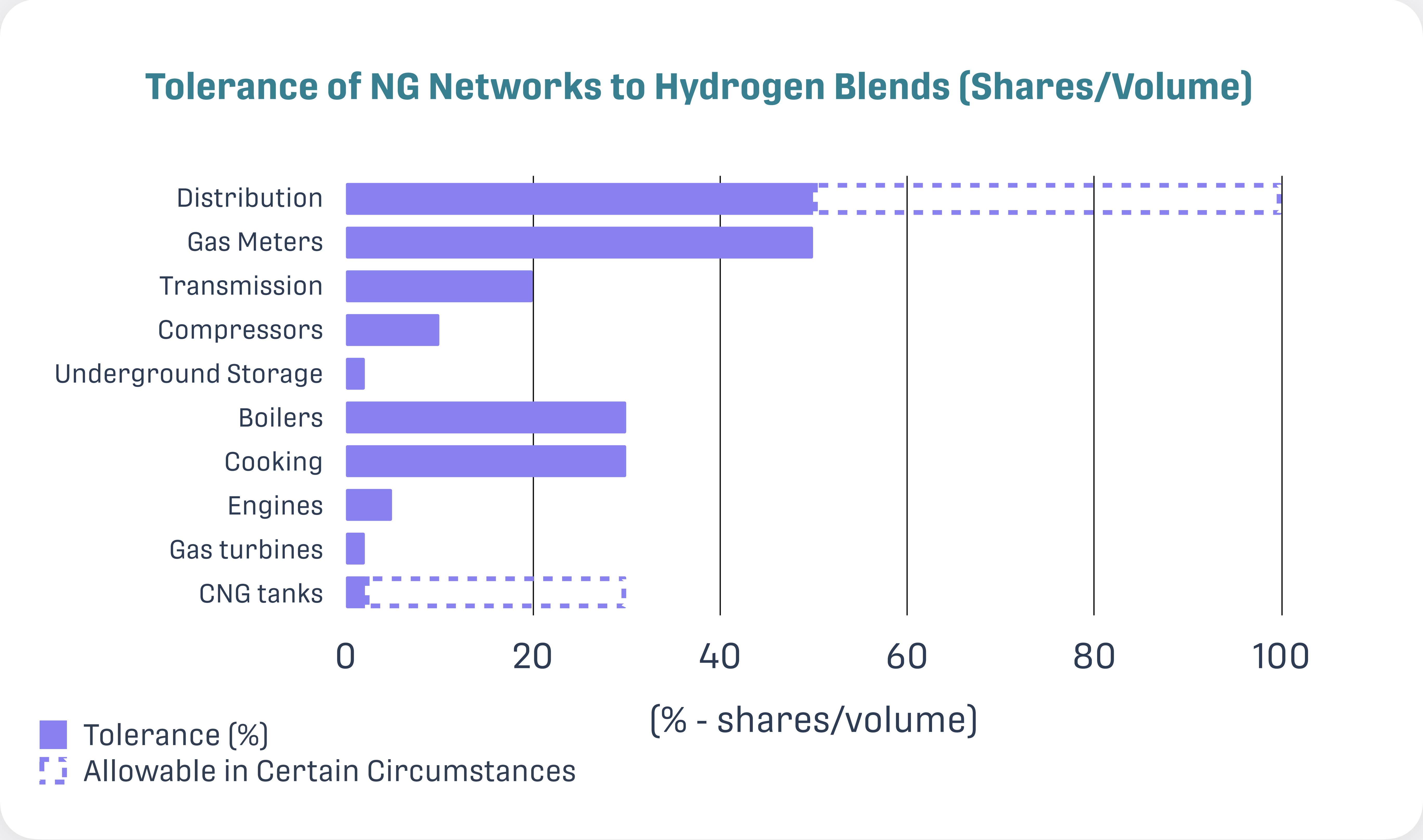
High-pressure tube trailers and LOHCs (liquid organic hydrogen carriers) or cryogenic hydrogen tanks

Like natural gas, pure hydrogen can be liquefied before it is transported to increase its density. However, liquefaction requires hydrogen to be cooled. If the hydrogen itself were to be used to provide this energy for cooling purposes, then it would consume around 25% to 35% of the initial quantity of hydrogen based on today's technologies. This is considerably more energy than is required to liquefy natural gas, which consumes around 10% of the initial quantity of natural gas. An alternative possibility is to incorporate the hydrogen into larger molecules that can be more readily transported as liquids. Options include ammonia and LOHCs. Ammonia and LOHCs are much easier to transport than hydrogen, but they often cannot be used as final products and a further step is needed to liberate the hydrogen before final consumption (except in cases where ammonia, for example, can be used directly by the final customer). This entails extra energy and cost, which must be balanced against the lower transport costs.

LOHCs are similar to crude and diesel, and so could use existing oil pipelines. However, the need to transfer the hydrogen carrier back to its place of origin to be reloaded with hydrogen, either by truck or a parallel pipeline operating in the opposite direction, makes this a complicated and expensive method of transport.

Blending with natural gas

Blending hydrogen into the natural gas infrastructure that already exists would avoid many of the significant capital costs involved in developing new transmission and distribution infrastructure. Most regulations allow introducing a maximum of 3% hydrogen blend into the natural gas transmission pipeline. Some existing components along the natural gas value chain have a high tolerance for hydrogen blending as shown in the figure below.



Source: IEA Hydrogen Report 2018

For example, polyethylene distribution pipelines can handle up to 100% hydrogen. Similarly, salt caverns can store pure hydrogen instead of natural gas without any need for upgrades. However, there are other parts of the existing natural gas value chain that cannot tolerate high levels of blended hydrogen. There is also the question of flammability since hydrogen burns much faster than methane, a key factor implying that new types of detectors would be required.

Variability in the volume of hydrogen blended into the natural gas stream would also have an adverse impact on the operation of equipment designed to accommodate only a narrow range of gas mixtures.

However, there are other parts of the existing natural gas value chain that cannot tolerate high levels of blended hydrogen. The biggest constraint is likely to be in the industrial sector, where many applications have not been certified or assessed in detail for hydrogen blending.

The control systems and seals of existing gas turbines are not designed for the properties of hydrogen and can tolerate less than 5% blended hydrogen. A similar issue arises for many installed gas engines, where the recommended maximum level of blended hydrogen is 2%.

Keeping track of how much hydrogen has been injected into the grid and its carbon intensity is also critical.

What's going on in the US?

As mentioned earlier, gaseous hydrogen can be transported through pipelines in much the same way natural gas is doing so today. Approximately 1,600 miles of hydrogen pipelines are currently operating in the United States. Owned by merchant hydrogen producers, these pipelines are located where large hydrogen users, such as petroleum refineries and chemical plants, are concentrated (like in the Gulf Coast region.)

Research today therefore focuses on overcoming technical concerns related to pipeline transmission, including:

- The potential for hydrogen to embrittle the steel and welds used to fabricate the pipelines.
- The need to control hydrogen permeation and leaks.
- The need for lower cost, more reliable, and more durable hydrogen compression technology.

Taking advantage of increasingly favorable regulations and a growing number of green policies throughout Europe, many startups are popping up in the transmission and distribution space, boosted by Germany's automotive leadership.

Startup Highlights

HY2GEN AG

Founded in 2017
Holzgerlingen, Germany.

Hy2gen aims to become the largest global producer of green hydrogen. Hy2gen develops and operates global production sites to secure a decentralized supply of carbon free hydrogen. Taking into account the energy price, market demand, logistics, and political environment, Hy2gen delivers stable green hydrogen supply at competitive pricing. Hy2gen is the first mover for commercial production and distribution of green hydrogen to a broad range of clients. The company delivers carbon free green hydrogen at required quality levels.

hydrogenious LOHC TECHNOLOGIES

Founded in 2013
Erlangen, Germany
Startup Autobahn EXPO8 Cohort

Hydrogenious Technologies develops innovative solutions for safe and efficient hydrogen storage in liquid organic hydrogen carriers.

The need for safe and efficient hydrogen storage for multi-MWh energy storage systems and safe and reliable hydrogen storage for hydrogen refueling stations and fuel cell mobility is imminent, and Liquid Organic Hydrogen Carriers (LOHC) have proven to be one the best solutions.

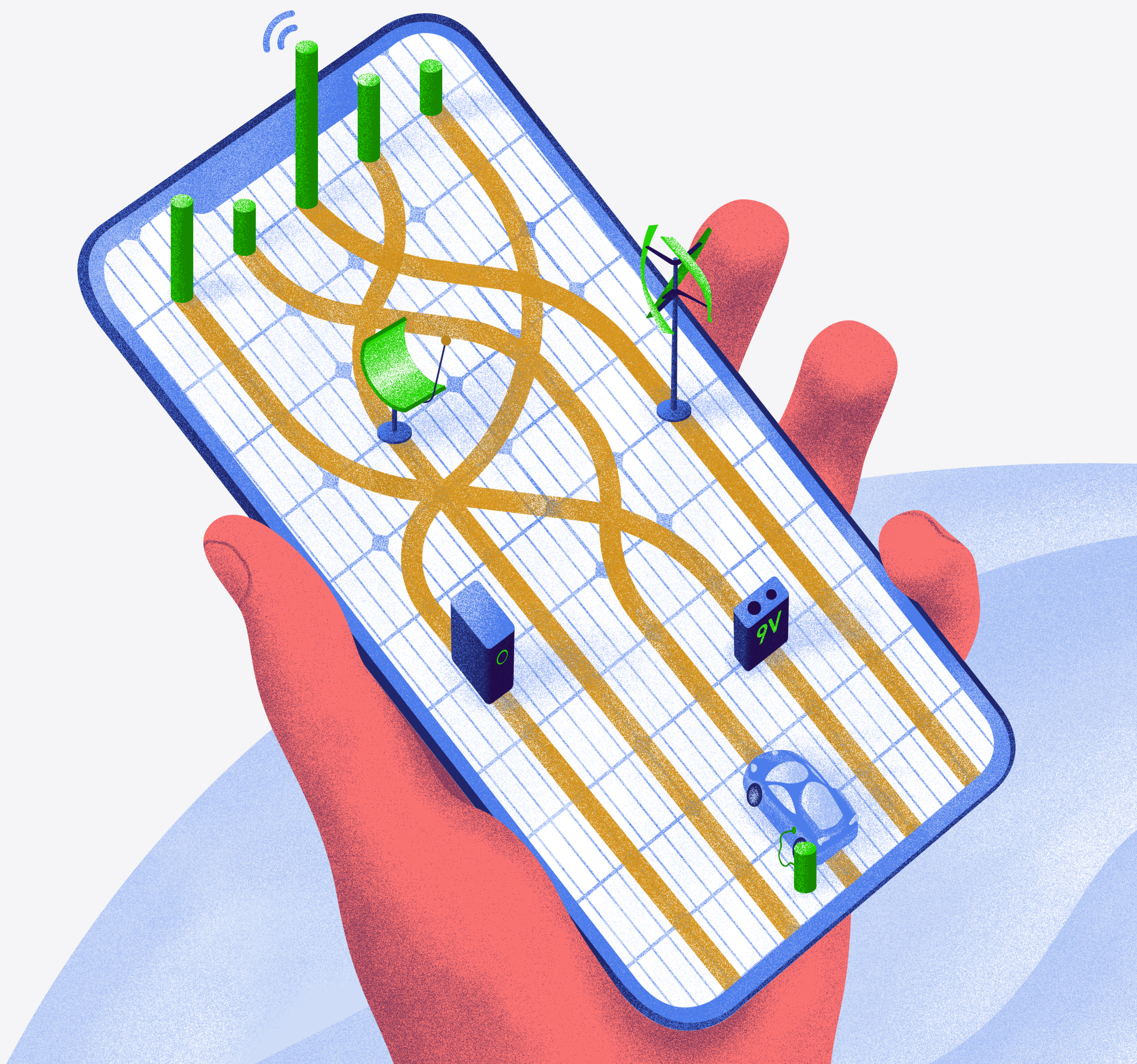
Hydrogenious’ LOHC systems enable high-capacity hydrogen handling in the existing fuel infrastructure through a reliable, economical system and with a small footprint. It can also link the sites where green hydrogen is most efficiently produced with the sites where it is consumed flexibly, simply, and at low cost.

Applications include refueling stations, industrial hydrogen, and sectoral integration.

Pilot Case Study with Hyundai CRADLE Through Startup Autobahn

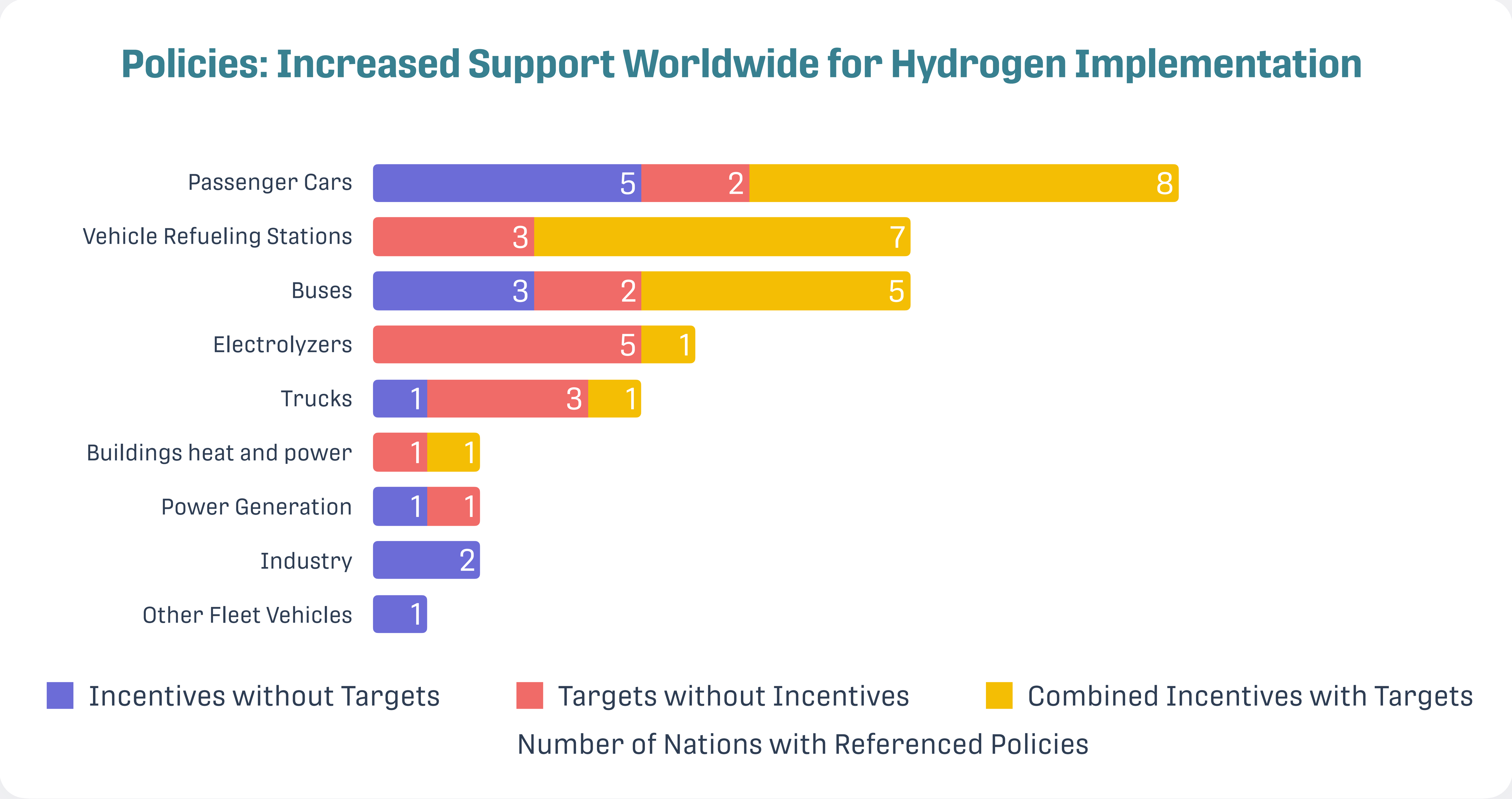
The distribution and transportation of hydrogen in large quantities is currently one of the biggest challenges Hyundai Motor Group is working on. Their Hyundai CRADLE office has partnered up with German startup, Hydrogenious LOHC Technologies, to work towards a sustainable, safe and cost-efficient transportation solution for hydrogen. LOHC technology allows hydrogen to be stored without pressure, using a carrier oil. This makes hydrogen as easy and efficient to transport as conventional liquid fuels and will enable distribution at the global scale both sustainably, and at a low cost. Currently, the teams are exploring opportunities for collaboration, which could include using their technology as a hydrogen logistic solution in Korea and Germany, leveraging on their frontier research activities with, for example, Jülich Forschungszentrum, or venturing into completely new fields of applications for LOHC.

The joint collaboration was fostered through Plug and Play's Startup Autobahn program and was first showcased at Startup Autobahn's EXPO8. Check out the video showcasing their collaboration here.



Policies

As the promise of useful advancements and adaptations of hydrogen technology continues to grow, the world's nations seek to foster expansion in this sector via government policies. Across North America, Europe, and Asia, many countries have adopted targets or incentives (or sometimes both) related to various predetermined milestones. A snapshot of the amount and types of policies is presented below.



Source: https://www.iea.org/reports/the-future-of-hydrogen

In addition to this form of support, certain areas have made a dedicated effort to actually putting capital forward to reach these goals. Globally, hydrogen use in transportation is expanding more quickly than ever, but still accounts for only half a percent of new low-carbon vehicle sales. The global fuel cell electric vehicle (FCEV) stock nearly doubled to 25,210 units at the end of 2019, with 12,350 new vehicles sold. This more than doubled the 5,800 purchased in 2018. In addition, at the end of 2019, 470 hydrogen refueling stations (HRS's) were in operation worldwide, an increase of more than 20% from 2018.

Japan currently remains the leader in stations, with 113, in addition to having adopted some of the most aggressive targets across the board. Korea, The Netherlands, and France are additional nations with similarly bullish goals. In the United States, a Hydrogen Posture Plan was adopted during the Bush Jr. administration with plans to appropriate $1.2Bn towards Hydrogen development. However in 2009 funds were reduced by roughly $100Mn per year, with Department of Energy Secretary Steven Chu stating that the technologies and improvements needed for applications such as fuel cells were not likely to be commercially viable in the near future. The number of HRS's in the U.S. lags behind both Japan and Germany, sitting at 64. Note that in California, a single HRS can range in cost from around $2.1Mn to about $3.0Mn.

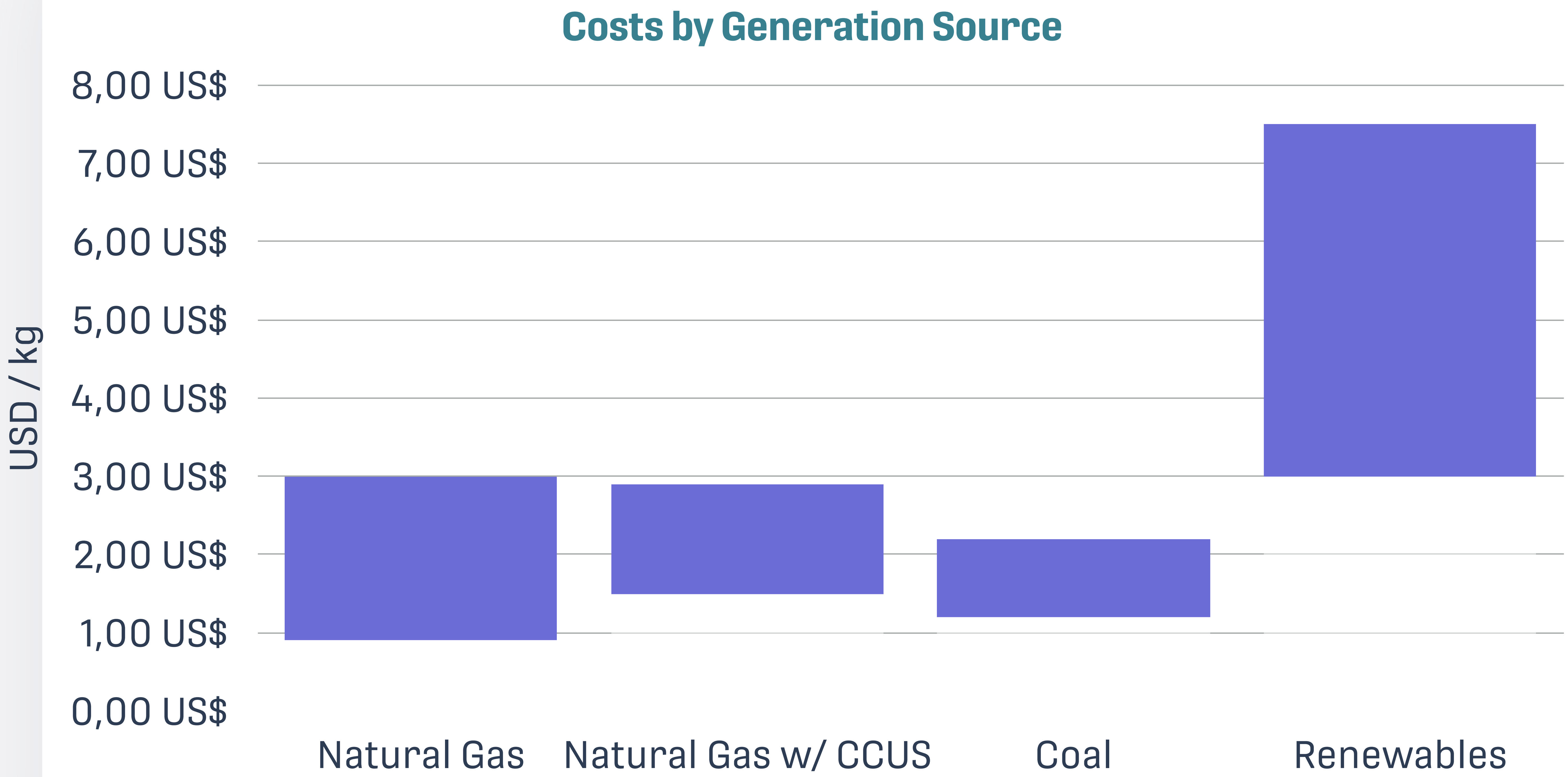
Fuel Cell Electric Vehicles: Current VS Goals

		Passenger Vehicles	Buses and Coaches	Trucks	Forklifts	Refueling Stations
US	Current	7.271	35 active, 39 in development	Prototype test	>30,000	~42 online
	Target		5,300,000 FCEVs on US roads by 2030		300,000 by 2030	7,100 by 2030
China	Current	0	2.000	1.500	2	23
	Target	3,000 by 2020 1,000,000 by 2030	11,600 commercial vehicles by 2020			100 by 2020 500 by 2030
Europe	Current	~1000	~76	~100	~300	~152
	Target	3,700,000 by 2030	45,000 fuel cell trucks and buses by 2030			~3700 by 2030
Japan	Current	3.219	18	N/A	160	127; 10 in progress
	Target	40,000 by 2020 200,000 by 2025 800,000 by 2030	100 by 2020 1,200 by 2030		500 by 2020 10,000 by 2030	160 by 2020 900 by 2030

Source: "Fueling the Future of Mobility: Hydrogen and fuel cell solutions for transportation" by Deloitte, published in Jan 2020, page 20

Cost Analysis

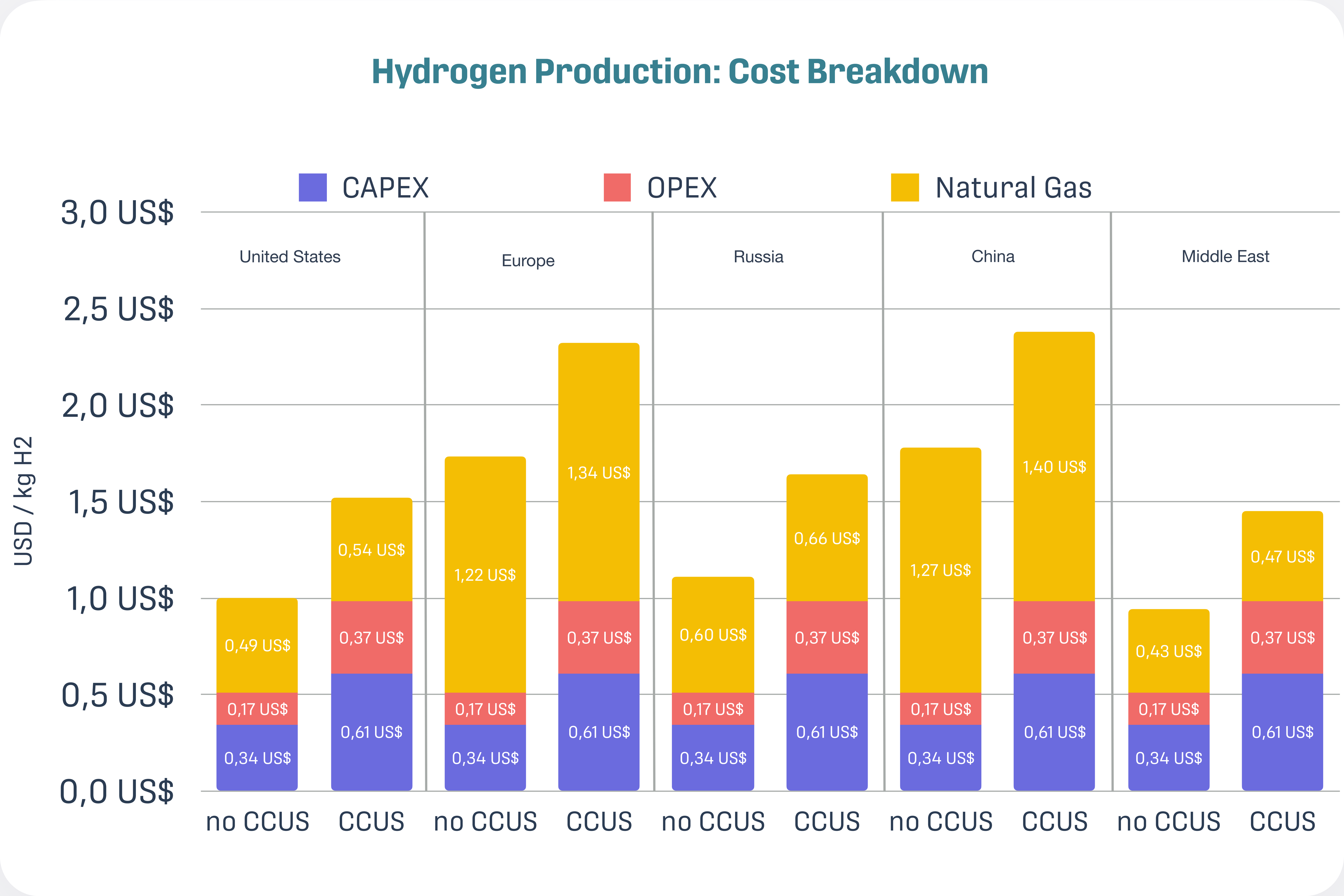
All the targets and good will in the world won't make up for the sheer economics behind hydrogen implementation however. With costs ranging from generation to transportation, storage, and finally even dispensing, it's important to obtain an understanding of how pricing factors into the equation at each step of the process. To start with, on the generation side it is important to note that green hydrogen produced through electrolysis is still significantly more expensive than hydrogen produced through steam methane reformation. An NREL study across 42 different wind sites demonstrated that base hydrogen costs ranged from $3.74/kg to $5.86/kg. These figures are above the U.S. Department of Energy 2015 targets of $3.10/kg (centralized) and $3.70/kg (distributed). Only with production tax credits and investment tax credits is wind-based hydrogen production within DOE targets. The key takeaway here is that coupling conventional technologies with carbon capture utilization and storage (CCUS) is still the main route for low-carbon hydrogen production and will likely remain so in the short to medium term. Still, the amount of projects and total electrolyzer capacity have increased considerably, from less than 1 MW in 2010 to more than 25 MW by the end of 2019.



Generation costs vary tremendously by source. Renewables w/ electrolysis are currently far behind fossil fuel based production.

Source

Looking at hydrogen produced from natural gas alone (which accounts for the majority of all production worldwide), one can split the costs into CAPEX, OPEX, and fuel costs to yield more insights. In the United States, the costs of CAPEX and OPEX involved in generation combined are roughly equivalent to the cost of natural gas alone. Despite how expensive it is in the States, these fuel costs are even more prohibitively expensive in Europe and China. In addition, we can see from the chart below that adding in CCUS will increase prices by 30%-50%.

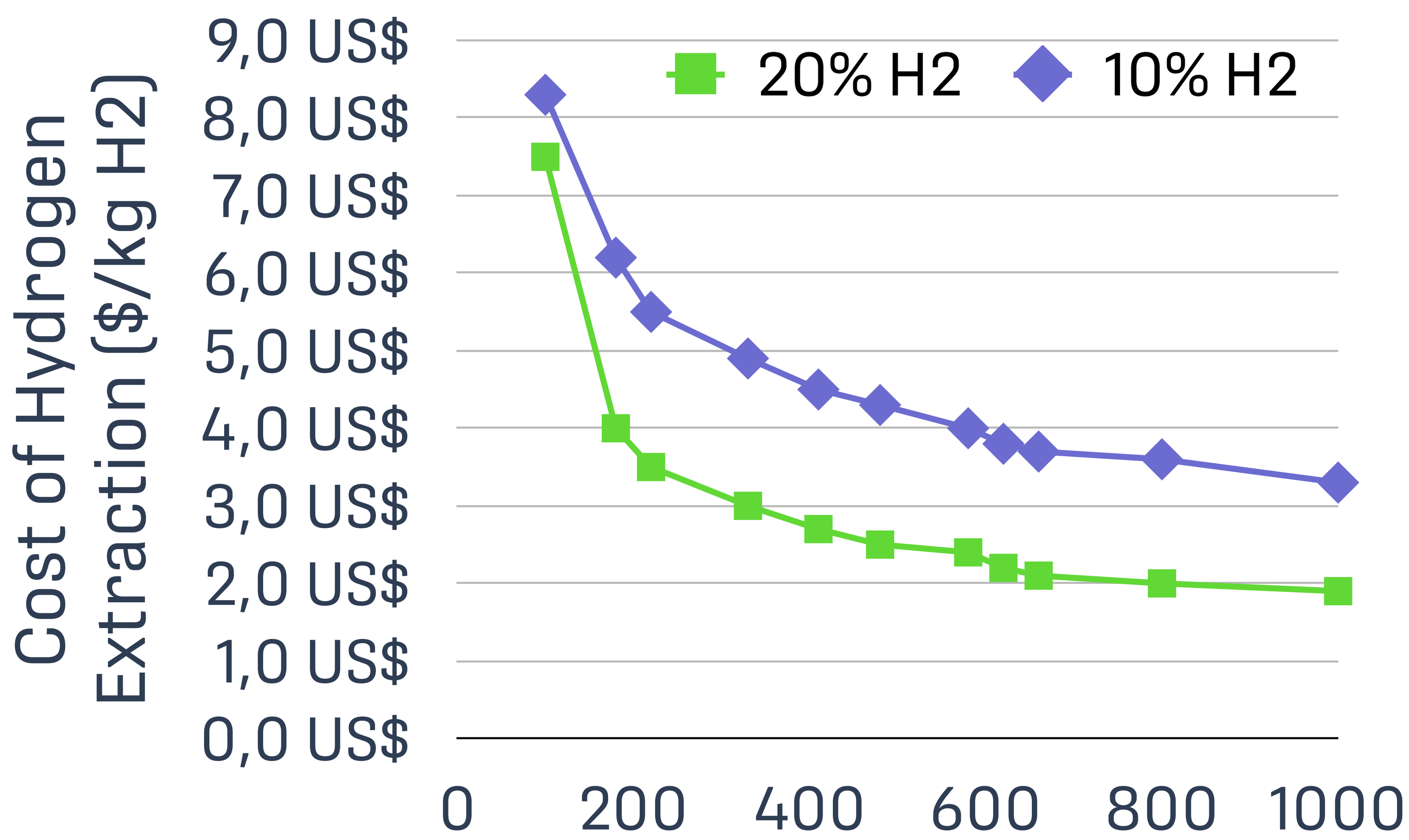


Source: https://www.iea.org/reports/the-future-of-hydrogen

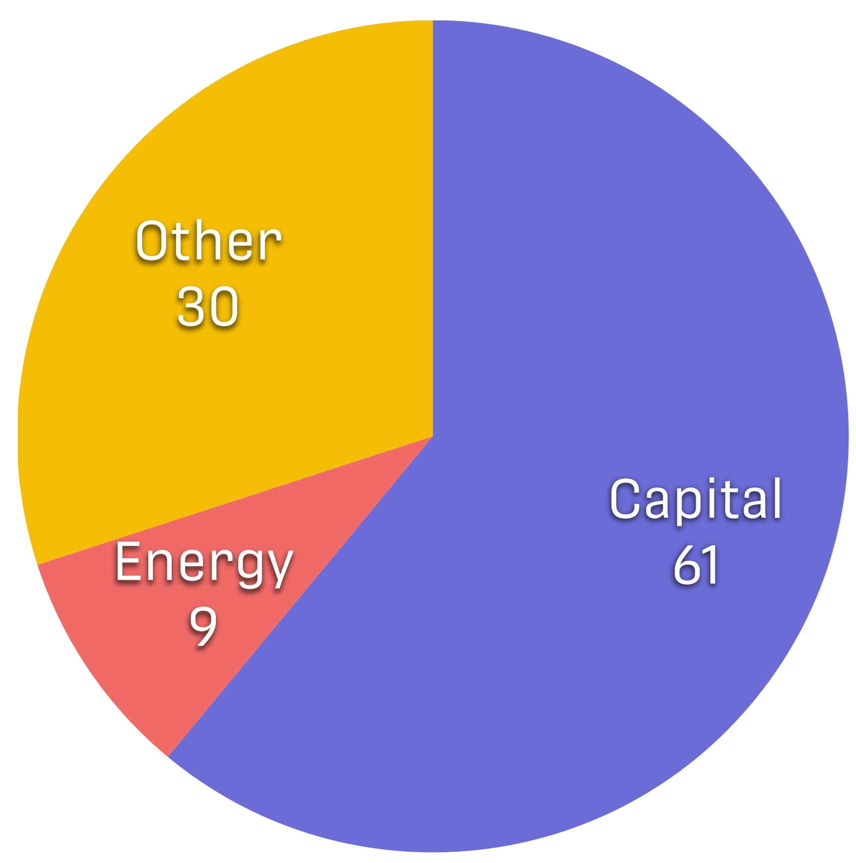
The production of hydrogen from a natural gas pipeline involves some fairly technical maneuvering. A pressure swing adsorption (PSA) device is utilized to separate a particular gas species from a mixture of gases under pressure according to the species' chemical and molecular characteristics. While this can be used to extract hydrogen at a pipeline (at say, 300 psi), the issue then becomes one of what to do with all the newly depressurized natural gas. This must be recompressed back into the pipeline.

Due to inherently low concentrations of hydrogen, the amount of natural gas that has to be recompressed is high and requires a large, expensive compressor. The key point is that compressor costs are potentially the highest in the whole process, even dwarfing labor and O&M. However, high recompression costs can potentially be avoided if hydrogen is extracted at a pressure-reduction facility so that the natural gas does not need to be recompressed. The following chart demonstrates the economies of scale of hydrogen extraction through use of a PSA unit at varying percentages of H2.

Cost of Hydrogen Production from Natural Gas Pipelines



Estimated cost of hydrogen extraction by PSA unit from 300 psi natural gas distribution pipeline with hydrogen recovery factor of 80%

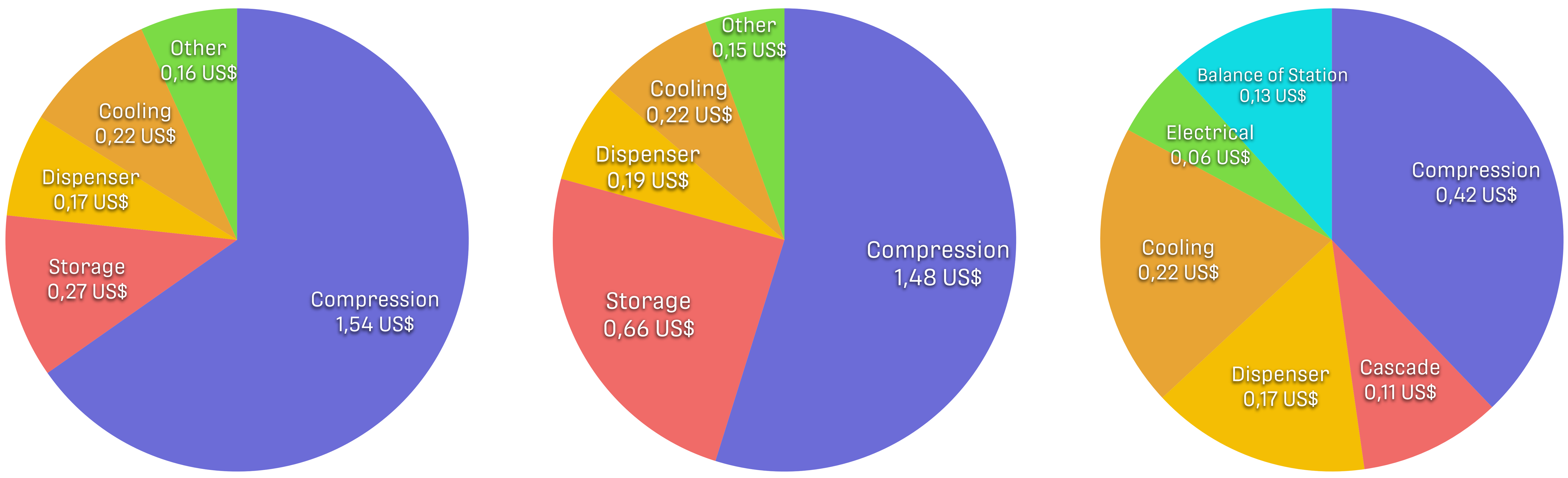


Hydrogen Extraction Cost Breakdown

Source: Blending Hydrogen into Natural Gas Pipeline Networks, NREL 2013; https://www.nrel.gov/docs/fy13osti/51995.pdf

Of course, we would be remiss if we didn't discuss the costs associated with storage. Below is a set of graphs demonstrating the cost breakdowns of the compression, storage, and dispensing (CSD) for pipeline, distributed, and tube trailer storage. Dispensing is simply that last step at the hydrogen fuel station where hydrogen is offered in a usable format.

What about Storage? Compression, Storage, Dispensing (CSD) Cost Breakdown



Cost Breakdown: Pipeline - $2.40/kg H2

Cost Breakdown: Distributed - $2.70/kg H2

Cost Breakdown: Tube Trailer - $1.12/kg H2

Source: Hydrogen Station Compression, Storage, and Dispensing Technical Status and Costs, NREL 2014; https://www.nrel.gov/docs/fy14osti/58564.pdf

Finally, putting these costs together we note that hydrogen retails for roughly $13.99 per kilogram. As a useful rule of thumb, one kilogram of H2 contains roughly the same amount of energy as one gallon of gasoline. However, a fuel cell is significantly more efficient than an internal combustion engine, and for this reason FCEVs are roughly twice as efficient as gasoline powered vehicles. Factoring in this efficiency, a kilogram of hydrogen is roughly equivalent on a price per energy basis to a $5.60 gallon of gasoline. According to NREL, H2 prices may fall to the $8/kg to $10/kg range by 2025. $8/kg is the crossover point, where hydrogen fuel would net $0.12 per mile compared to $0.13 per mile provided by $3.50 per gallon of gasoline. If the costs can be brought down by this significant margin, hydrogen vehicles will have a serious chance of displacing older styles of cars.

Still, it's important to note that criticisms abound when it comes to FCEVs, especially when compared to more feasible electric vehicles (EVs). We have already seen that most hydrogen is not produced through electrolysis, which remains extremely expensive. For this reason, EVs are also currently seen by many as being greener overall than FCEVs. A 2016 study in the journal Energy by scientists at Stanford University and the Technical University of Munich concluded that, even assuming local hydrogen production,"investing in all-electric battery vehicles is a more economical choice for reducing carbon dioxide emissions, primarily due to their lower cost and significantly higher energy efficiency." Even more brutally, a 2017 analysis published in Green Car Reports found that the best FCEVs consume "more than three times more electricity per mile than an electric vehicle... generate more greenhouse-gas emissions... [and have] very high fuel costs. Considering all the obstacles and requirements for new infrastructure (estimated to cost as much as $400 billion), fuel-cell vehicles seem likely to be a niche technology at best, with little impact on U.S. oil consumption."

Regardless of these criticisms, significant momentum is already pushing the trend forward. While the future of hydrogen fuel in our society remains uncertain, it is clear that keeping an eye on the relevant developments will remain important for those wishing to keep a more exacting view on our energy and mobility landscape. Perhaps our readers who have made it this far will play an integral role in this burgeoning space. Only time and a bit of creativity will tell.

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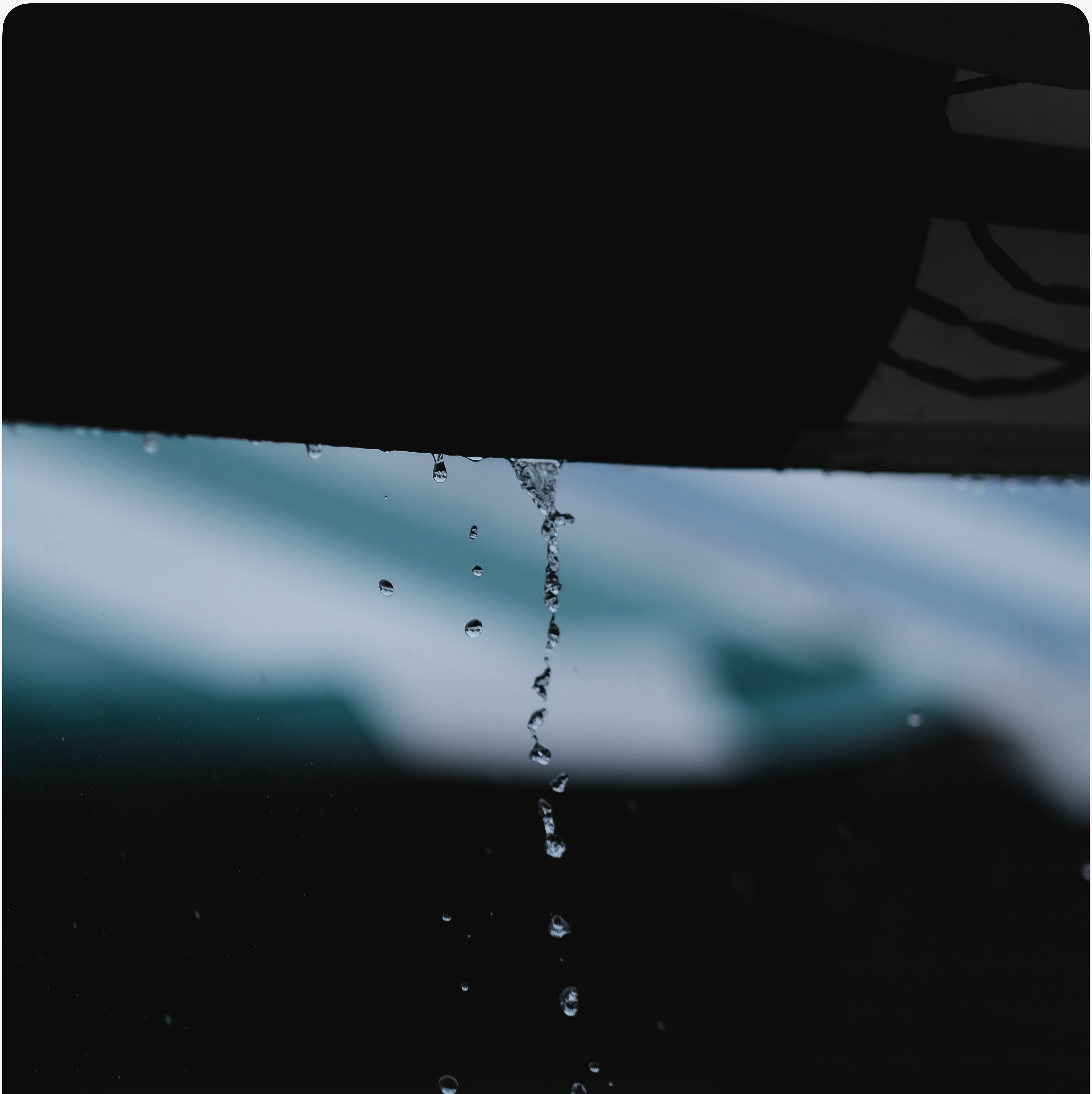

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