PG&E GAS R&D AND INNOVATION

WHITEPAPER

Pipeline Hydrogen

9/18/2018

Together, Building
a Better California

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Summary: Hydrogen

Definition: Hydrogen is the first chemical element on the periodic table, and is both the smallest and lightest element in the universe, as well as the most abundant. In its pure form, hydrogen (H_2) is a colorless, odorless, tasteless, non-toxic, and highly combustible gas. Hydrogen can be found in combination with other elements, such as H_2O or CH_4, but does not exist by itself freely in nature. It is only produced from other sources of energy, so it is often referred to as an energy carrier. Hydrogen needs be isolated or "produced" by breaking the chemical bonds in the molecules that form these substances – usually by steam reforming natural gas (methane) or through the electrolysis of water. Hydrogen is relevant to PG&E through its use directly as a fuel, as a feedstock for RNG, or blended with natural gas.

Figure 1 Hydrogen from Water Electrolysis (Albert Albert, 2017)

Importantly, hydrogen is not itself a greenhouse gas (GHG), nor does it produce GHGs when burned, making it a potential substitute for reducing the carbon intensity or pollution of some energy or fuel applications. PG&E has a unique opportunity to leverage the nature of its integrated natural gas and electric business to explore several of applications for hydrogen as part of its push to reduce GHG emissions by 80% from 1990 levels by 2050.

POTENTIAL OPPORTUNITIES FOR PIPELINE HYDROGEN:

1. *Near Future* – **Fuel for Light Duty Hydrogen FCEVs**
2. *Near Future* – **Small-Scale Blending with Pipeline Natural Gas**
3. *Near Future* – **Short-Term Storage of Curtailed Renewable Electric Energy**
4. *Near Future* – **Fuel/Catalyst for Renewable Natural Gas Generation**
5. *Long-Term* – **Delivery of Hydrogen for Residential Fuel Applications**
6. *Long-Term* - **Fuel for Heavy Duty Hydrogen FCEVs**
7. *Long-Term* – **Seasonal Storage for Electric Grid**

Blending hydrogen with natural gas in the utility pipeline system is not new – in fact, manufactured gas in the 1800s produced from coal, pitch, whale oil, or petroleum contained 30-50% hydrogen. This gas, called "town gas" or “water gas”, was used in the United States until the last manufactured gas plant in New York was shut down in the early 1950’s (Melaina, 2013). However, modern gas pipeline systems since then have been optimized to transport methane, and the introduction of hydrogen at large scale would necessitate at least some change to the current system, especially to pipeline monitoring and integrity management practices. Because of Hydrogen’s corrosive and embrittlement effects on some metals (DNV GL, 2018), PG&E must evaluate the gas pipeline system end-to-end for hydrogen’s potential effects on the system and the resulting implications for public and employee safety.

While Hydrogen has obvious applications in the energy and transportation markets, nearly all hydrogen produced in the US is currently used in fossil fuel refining, treating metals, producing fertilizer, and processing foods. California is one of the top producers of hydrogen in the US (along with Louisiana and Texas), but very little of that Hydrogen is used directly as a transportation fuel or as a direct source of electricity, and it is transported through dedicated hydrogen pipeline systems. A major barrier to the adoption of hydrogen in the natural gas pipeline system is simply the newness of the idea of injecting hydrogen into pipelines optimized for natural gas.

Finally, both the generation and demand of hydrogen is subject to significant competition in the market, particularly in demand, where hydrogen competes in a crowded field of market entrants as a transportation fuel, source of electric generation, residential heating and cooking, or form of storage. While the field is crowded, however, hydrogen has a good case to be made in each segment, which is why it is under consideration today as a potential alternative, GHG-free fuel for pipeline injection.

More Resources on Pipeline Hydrogen and Hydrogen as a Fuel:

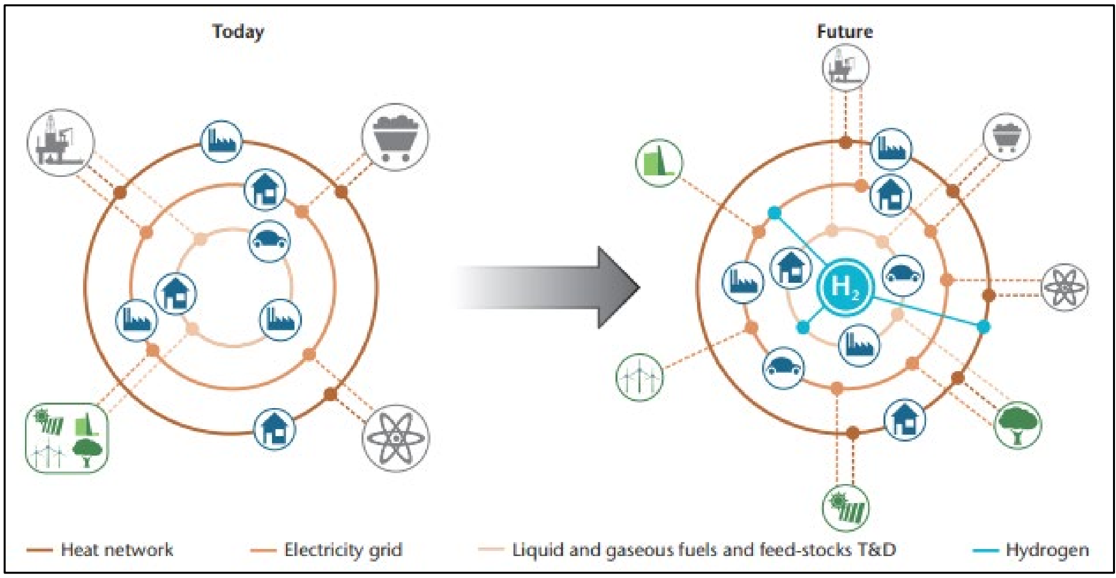
Hydrogen Council: Hydrogen Scaling Up – A Roadmap to 2050
California Hydrogen Business Council: Renewable Hydrogen Roadmap
International Energy Agency: Technology Roadmap Hydrogen and Fuel Cells
US DOE: Overview of Natural Gas Conversion Technologies for Co-Production of Hydrogen and Value-Added Solid Carbon Products
NREL: California Power-to-Gas and Power-to-Hydrogen Near-Term Business Case Evaluation

Pipeline Hydrogen – Market Potential

Included here are different forecasts for the potential for hydrogen in its various market segments. Perhaps other places in the world – Europe - how much hydrogen is in the pipeline system now? Include market sizing if possible.

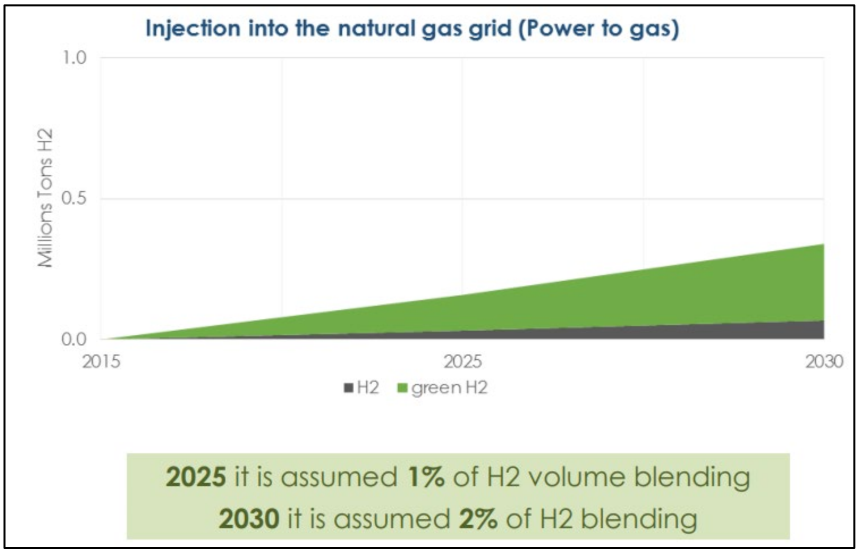
Today, the industry sector represents over 99% of the entire hydrogen market. Major consumers of hydrogen are petroleum refining (47%) and fertilizer production (45%). The US alone produces 10 million metric tons of hydrogen each year, and steam methane reformation accounts for 95% of that production. (Fraile, 2015)

In the future, hydrogen could play a significant role in connecting different layers of infrastructure in a low-carbon energy system. The market potential of hydrogen as a fuel is closely linked to the advancement of hydrogen fuel cells and electrolyzers with large opportunities for it to be used on a large scale in renewable electricity integration, power-to-gas, and eventually for mobility. Global demand is expected to grow from 43 Mtons in 2010 to 53 Mtons by 2030 with Europe representing 16% of the hydrogen global market. (Fraile, 2015)



Comparison of the energy system today and in the future (International Energy Agency, 2015)

The Hydrogen Council estimates that by 2030, 230-250 TWh of surplus solar and wind energy will be converted to hydrogen (Hydrogen Council, 2017). As much as 1/5th of total energy consumed by 2050 can be from hydrogen (Mehta, 2018). Countries have made commitments to advance and promote hydrogen as a fuel. Following the tsunami and nuclear disaster, Japan announced that the 2020 Tokyo Olympics will showcase thousands of hydrogen fuel cell vehicles. (Mehta, 2018) A Toyota plant that is manufacturing fuel cell stacks already. Japan will import hydrogen, with Australia being a front-runner, using plentiful coal supply to make hydrogen and capturing the resulting carbon dioxide emissions. In Europe, transportation demand for hydrogen is expected to be concentrated in light-duty vehicles, mainly in Germany and the UK.



Estimated hydrogen injection based on 1% and 2% blending (International Energy Agency, 2015)

The demand by market segment will be dependent on the strength of the regulatory framework and market incentives. It is also dependent on the ability to produce hydrogen cost effectively.

Hydrogen Generation

Hydrogen can be generated from diverse resources – though primarily fossil fuels, biomass, or electricity and water. The challenge is to separate hydrogen (which does not occur naturally by itself) from its naturally occurring compounds efficiently, and economically. In addition, the environmental impact and energy efficiency of hydrogen varies with the method of production.

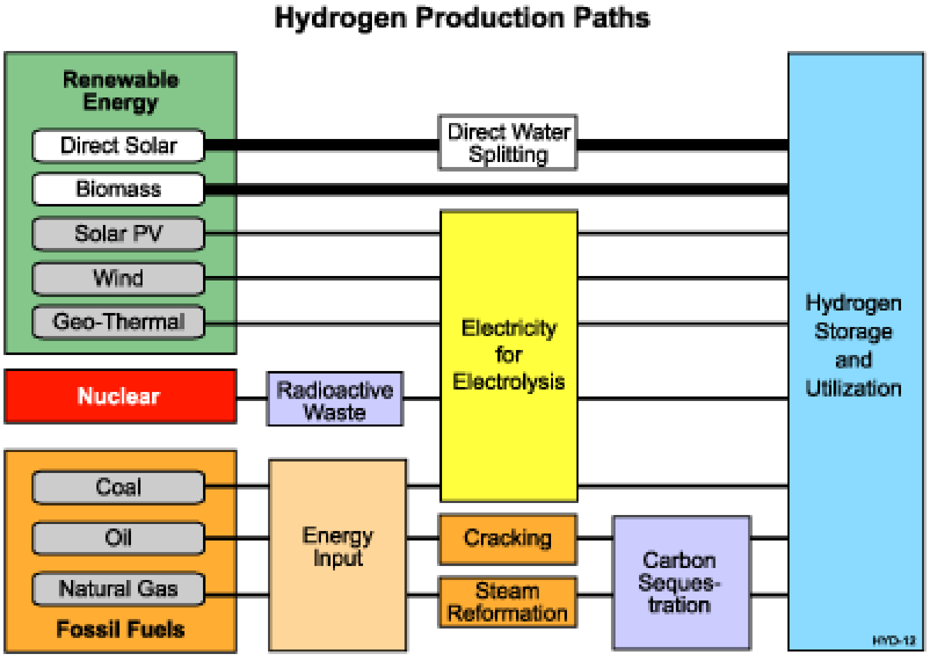


Figure 2 Hydrogen Production Paths (University of Central Florida, 2014)

In recent years, a variety of methods for separating hydrogen have cropped up, but the vast majority of mature hydrogen separation systems can be categorized as steam reforming, or electrolysis, using natural gas or electricity as the feedstock respectively (Florida Solar Energy Center, 2004). Below is an overview of these two technologies, as well as a summary of some of the other potential technologies emerging for the production of hydrogen.

STEAM METHANE REFORMING

Steam reforming is the most commonly used, and mature means of hydrogen generation, and produces about 95% of all the hydrogen used commercially in the United States (Florida Solar Energy Center, 2004). The process uses water (steam) and natural gas to produce synthetic gas through *reformation* – where methane reacts with high temperature steam in the presence of a catalyst to produce an endothermic reaction generating CO and H_2. The remaining CO is then put through the *water-gas shift reaction* to generate CO_2 and additional H_2. When CO_2 and other impurities are cleaned from the gas stream (usually using pressure-swing absorption), the remnants are essentially pure hydrogen. The chemical formulas for these processes are below. (PG&E R&D and Innovation, 2018)

Figure 3 Steam Methane Reformation Path (PG&E R&D and Innovation, 2018)

Steam-methane reforming reaction

$$CH_4 + H_2O \text{ (+ heat)} \rightarrow CO + 3H_2$$

Water-gas shift reaction

$$CO + H_2O \rightarrow CO_2 + H_2 \text{ (+heat)}$$

Hydrogen produced by steam methane reforming can be approximated by 3x the cost of natural gas per unit of energy produced (Florida Solar Energy Center, 2004). Therefore, if natural gas is at $3/MMBTU, then the resulting hydrogen should cost in the ballpark of $9/MMBTU. Electrolysis has a lower multiple compared to the electricity used for the process, but the electric prices per unit of energy in California is often much higher, meaning that independent of other value streams, steam methane reforming is cheaper than electrolysis in California.

Steam reforming units are usually quite large, due to the need for economies of scale to compensate for the technology's use of high pressures (200-600 psi) and high temperatures (800-925 °C) (Wikiwands Methane Reformer, 2018). Therefore, some in the fossil fuels industry are considering R&D into smaller units to produce hydrogen as fuel cell feedstock. Current efforts involve reforming methanol instead of methane (Wikiwands Steam Reforming, 2018). If such a technology could be developed for methane reforming, the flexibility and smaller size of the system might have helpful applications for PG&E.

Steam reforming unit open in 2012 by Air Liquide in La Porte (TX)

However, for PG&E's purposes, this is primarily of use as a means of separating Hydrogen from Natural Gas at the point of energy demand, ***not*** *as generation in and of itself.* Because the source of hydrogen in this case is usually methane, without carbon capture, this form of hydrogen generation still produces exactly as much CO_2 as the burning of regular natural gas, but with less efficiency (because of the energy needed to separate the hydrogen). However, if the source of methane is renewable (electrolysis and methanation, or biomethane), reformation can be effectively used to generate hydrogen from pipeline natural gas without adding to net GHG emissions.

POWER-TO-GAS (P2G) / ELECTROLYSIS

Power-to-gas (P2G) is an umbrella term for technologies that convert electrical energy into gas fuel, most commonly hydrogen gas (Wikiwand Power-to-Gas, 2018). P2G is important to PG&E for 2 major reasons: If the electrical energy converted to gas is renewably generated (say from wind or solar), then the gas generated is also renewable in nature, potentially reducing the GHG intensity of gas generated by PG&E. PG&E is also uniquely optimized to explore these technologies because it is an integrated gas and electric utility. It can maximize the benefits of P2G not just for gas, but also to the electric grid, particularly the added-value of the gas system as high-capacity storage for an electric generation portfolio increasingly dominated by renewable energy.

While there are several mechanisms for generating power to gas, the most common and mature technology for Hydrogen generation is *Electrolysis*:

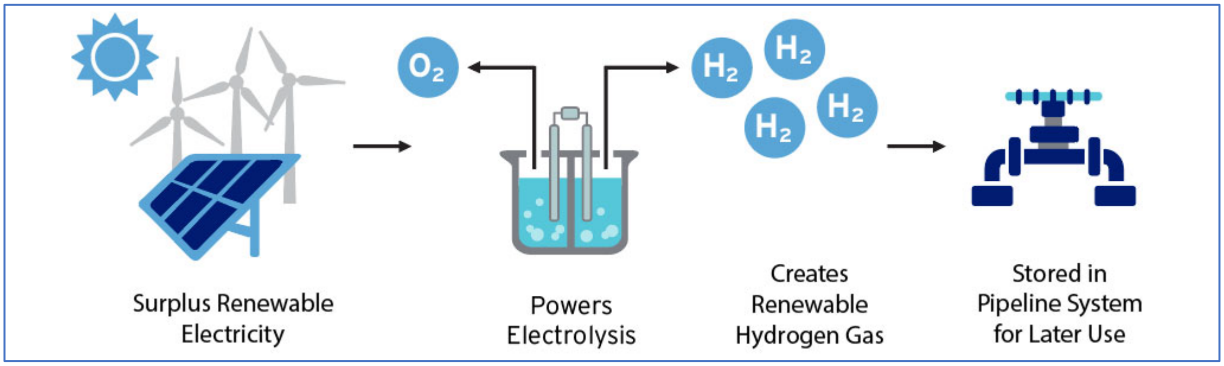


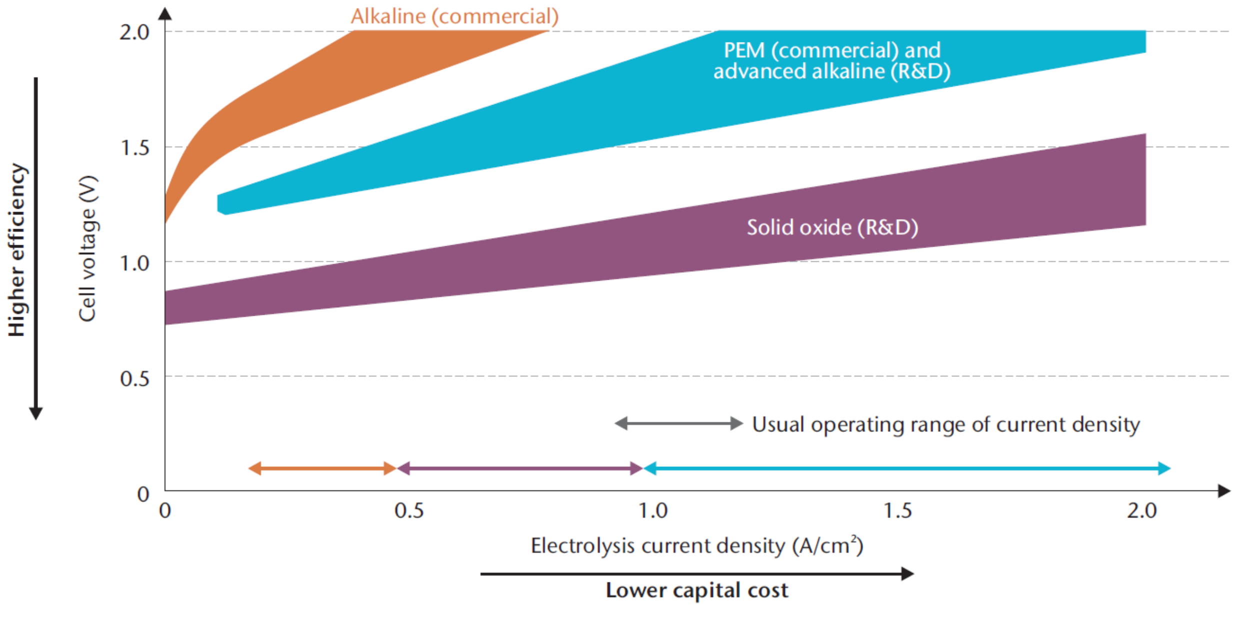
Figure 4 Path of Electrolysis (SoCalGas, 2018)

Electrolysis uses an electric current to split water into hydrogen gas and breathable oxygen. This reaction takes place in an electrolyzer. Most electrolyzers consist of two electrodes or plates that are placed in water, and a DC electric current is connected to both sides. Hydrogen appears at the cathode (where the electrons enter the water) and oxygen forms at the anode. The efficiency of this process can be increased by adding an electrolyte (like salt) to the water or through the use of electro-catalysts. (Wikiwand Electrolysis of Water, 2018) There are three main types of electrolyzers as shown in the table below.

Table 1 Types of Electrolyzers (PG&E R&D and Innovation, 2018)

Electrolyzer	Description
PEM Electrolyzers	Polymer material electrolyte – At the anode, water reacts to form oxygen and positively charged hydrogen ions (protons). The electrons flow through an external circuit and the hydrogen ions selectively move across the PEM to the cathode. At the cathode, hydrogen protons combine with electrons from the external circuit to form hydrogen gas. **Anode Reaction:** $2H_2O \rightarrow O_2 + 4H^+ + 4e^-$ **Cathode Reaction:** $4H^+ + 4e^- \rightarrow 2H_2$
Alkaline Electrolyzers	Liquid Alkaline Electrolyte Solution of Sodium or Potassium Hydroxide – Alkaline electrolyzers operate via transport of hydroxide ions (OH-) through the electrolyte from the cathode to the anode with hydrogen being generated on the cathode side.

	***Note:** Newer approaches using solid alkaline exchange membranes as the electrolyte are showing promise on the lab scale.
Solid Oxide (SO) Electrolyzers	Solid Ceramic Material Electrolyte – At the cathode, water combines with electrons from the external circuit to form hydrogen gas and negatively charged oxygen ions. The oxygen ions pass through the solid ceramic membrane and react at the anode to form oxygen gas and generate electrons for the external circuit. Solid oxide electrolyzers need to operate at 700°– 800°C, compared to PEM electrolyzers, which operate at 70°– 90°C, and commercial alkaline electrolyzers, which operate at 100°–150°C.



Note: A/cm² = ampere per square centimetre.

Until recently, hydrogen had never been used in a power-to-gas application with injection into the natural gas pipeline system in a real application within the United States. However, in 2016, UC Irvine in partnership with Southern California Gas Company launched a pilot project demonstrating the use of power-to-gas through electrolysis, that injects hydrogen directly into UC Irvine's natural gas pipeline system. While P2G systems are in use in Germany, the UK, and Canada, this is the first such project in the United States. (UCI, 2016)

More Information on Hydrogen Injection Projects:

UC Irvine: In A National First, UCI Injects Renewable Hydrogen into Campus Power Supply

Fuel Cells Bulletin: UC Irvine injects P2G green hydrogen into campus power supply
UK HyDeploy Project: Injecting Zero-Carbon Hydrogen into UK Pipelines
Juniper 1000 Project: https://www.jupiter1000.eu/english

OTHER SOURCES OF HYDROGEN

There are many ways of generating hydrogen, and while Steam Methane Reforming and Electrolysis are by far the most common and mature, many other methods do exist in various stages of development. Below are listed several other means of Hydrogen Generation. For more information on each of these methods, *please see PG&E R&D Technical Analysis on Hydrogen* (PG&E R&D and Innovation, 2018).

1. Tri Generation
2. Partial Oxidation
3. Chlorine-Alkaline Electrolysis
4. Internal Combustion Assistance On-Board Hydrogen Generator
5. Nanotech for Hydrogen from Sunlight
6. The Linde Group
7. Air Products, Hydrogen Plants
8. Compact Hydrogen Generator
9. Combined Heat, Hydrogen and Power (CHHP) System

Pipeline Hydrogen

The use of hydrogen gas as a renewable and practical energy carrier partly depends on whether it can be distributed safely and efficiently to consumers. The existing natural gas piping infrastructure could provide that means if it is compatible. However, a network designed for natural gas can't be used for pure hydrogen without major modifications to network components or the way it is operated and maintained. The existing natural gas transmission, distribution and end use systems *could* be used for mixtures of natural gas and hydrogen given appropriate adaptations. (PG&E R&D and Innovation, 2018)

The key concern with hydrogen injection into a utility natural gas pipeline system is safety, especially in regards to the integrity management of the pipeline infrastructure. While the performance of the gas in end-use appliances is of significant concern, it will be addressed separately below in *Demand for Hydrogen.* The physical and chemical properties of hydrogen differ from natural gas, so adding a certain percentage of hydrogen may impact combustion properties, diffusion into pipeline materials, carbon steel oxidation, and how the gas mixture behaves in air. In order to achieve a reasonable expectation of safety, many steps must be taken by the natural gas utility to inspect and fortify the system to match the needs of hydrogen injection (*please see Summary: Hydrogen*). Most notable among these topics are *Hydrogen Blending Standards* and *Hydrogen Embrittlement*. (PG&E R&D and Innovation, 2018)

HYDROGEN INTERCONNECTION/STANDARDS:

According to the International Energy Agency (IEA), blending hydrogen in the natural gas pipeline system necessitates, “upper blending limits of around 20% to 30%, depending on the pipeline pressure and regional specification of steel quality.” This is primarily due to Hydrogen’s ability to embrittle steel, or more precisely, accelerate crack growth particularly in steel welds. (International Energy Agency, 2015)

Additionally, since Hydrogen has a much lower energy density than Natural Gas[1], more volume of hydrogen is needed to generate the same amount of energy as natural gas. At 20% volumetric blend share, flow rate needs to be increased by around 15% to provide the same energy to the customer.” Maximum allowable operating pressure standards (MAOP), Hydrogen’s tendency to embrittle and accelerate crack growth in steel welds, and hydrogen’s performance at the point of customer demand combine to throttle the potential upper limits of hydrogen blending without significant infrastructure adjustments. (International Energy Agency, 2015)

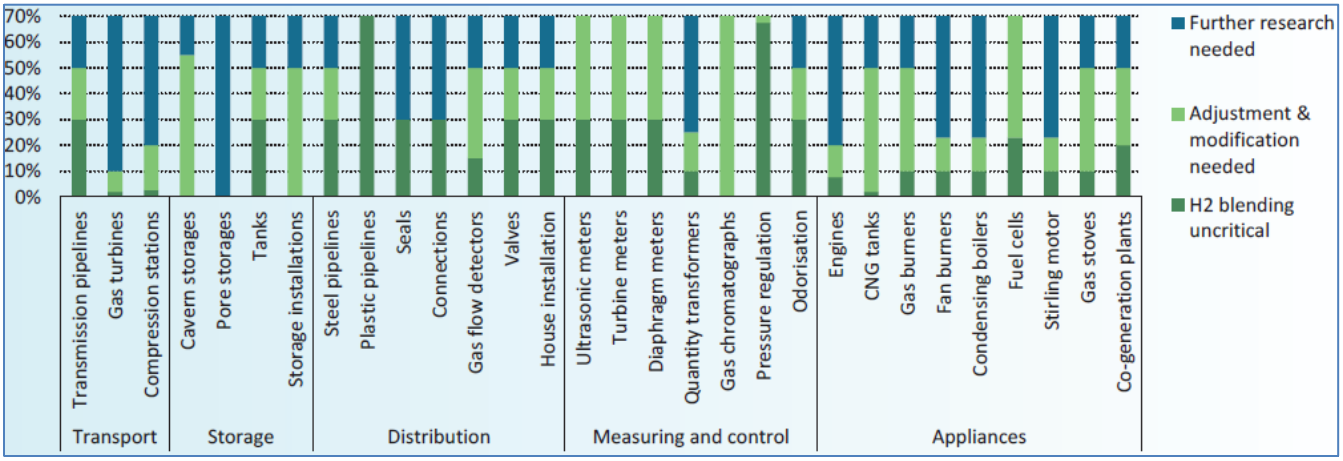


Figure 5 Limitations on the blend share of hydrogen by application – the most important applications to the blend share are gas turbines, compressing stations and CNG tanks. (PG&E R&D and Innovation, 2018)

According to a GTI study, “Blending Hydrogen into Natural Gas Pipeline Networks: A Review of Key Issues,” a quantitative risk assessment indicated blending of hydrogen up to 20% in distribution mains and services was not significant. That same study indicated that up to 50% blended hydrogen would have a moderate risk increase on average, but that in some discrete areas, the risk could be quite severe, and anything above that level becomes prohibitive with distribution mains and services designed for natural gas. (Melaina, 2013)

HYDROGEN LEAKS/ODORIZATION

Because Hydrogen is so small and mobile, it can more easily permeate seals and plastic pipe than methane. In general, the volume leakage of hydrogen is estimated at around triple that of natural gas (Melaina, 2013), which is

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[1] High Heating Values per unit of volume are for Methane $40MJ/m^3$, for Hydrogen $13MJ/m^3$

negligible in economy-scale terms. However, one or many concentrated leaks in a confined area might raise the levels of hydrogen to an unacceptably high level, which would be a significant safety concern. However, at the moment, there is no odorant for hydrogen, which makes detection of significant or hazardous concentrations of hydrogen by customers, employees, or the public very challenging (Melaina, 2013). Additionally, hydrogen monitoring and leak detection tools become increasingly important as concentrations of hydrogen in the pipeline increase.

HYDROGEN TOLERANT PIPELINE/METERING

At the distribution level, even large amounts of hydrogen do not pose significant issues. Hydrogen does not have notable integrity management issues with PVC or PE pipe. GTI determined that even gas metering is still within acceptable calibration limits (within 4%) of gas mixtures with an upper limit of 50% (Melaina, 2013).

However, hydrogen concentrations are a *significant* integrity management issue in Transmission pipeline infrastructure. In particular, hydrogen is known to cause *hydrogen-environment embrittlement (H-E)* or *cracking* in the welds of steel transmission pipelines. This is the degradation of mechanical properties when metal is exposed to a hydrogen environment. It occurs when the metal is under stress and cracks are present. Specifically, Hydrogen gas reduces the fracture toughness, crack propagation resistance, and ductility (as measured by reduction in area), and increases the fatigue crack growth rates for pipeline steels and their welds. For more information on each of these elements of embrittlement as well as the limits of each, *please see the PG&E R&D Hydrogen Technical Analysis* (PG&E R&D and Innovation, 2018).

Demand for Hydrogen

The demand for hydrogen is a crucial input to the development of the hydrogen economy. However, many of the technologies involved in creating a market for pipeline hydrogen are less mature and involve a great deal more uncertainty than other segments of the hydrogen supply chain.

Hydrogen is fighting for acceptance in a competitive market for transportation fuel (and sometimes the resulting LCFS credits) with fossil fuels, electricity, and energy efficiency. In the energy storage space, it must compete with lithium ion batteries and other forms of energy storage. In power generation, it competes with natural gas, and renewable energy to provide clean power to utility customers. This means that the development of the market for hydrogen is affected significantly both by timing and the development of ancillary markets. (International Energy Agency, 2015)

Of these potential sources of demand for pipeline hydrogen, the most likely development pathway is likely to be one or a combination of fuel for *hydrogen fuel cell vehicles (FCEVs)*, a source of seasonal storage for renewable electricity, a source of renewable natural gas, or as a low-carbon blended gas with methane for residential heating and cooking applications. (International Energy Agency, 2015)

Below is a graphic from the US National Renewable Energy Laboratory (NREL) on the hydrogen supply chain and various potential uses for hydrogen in the modern energy economy:

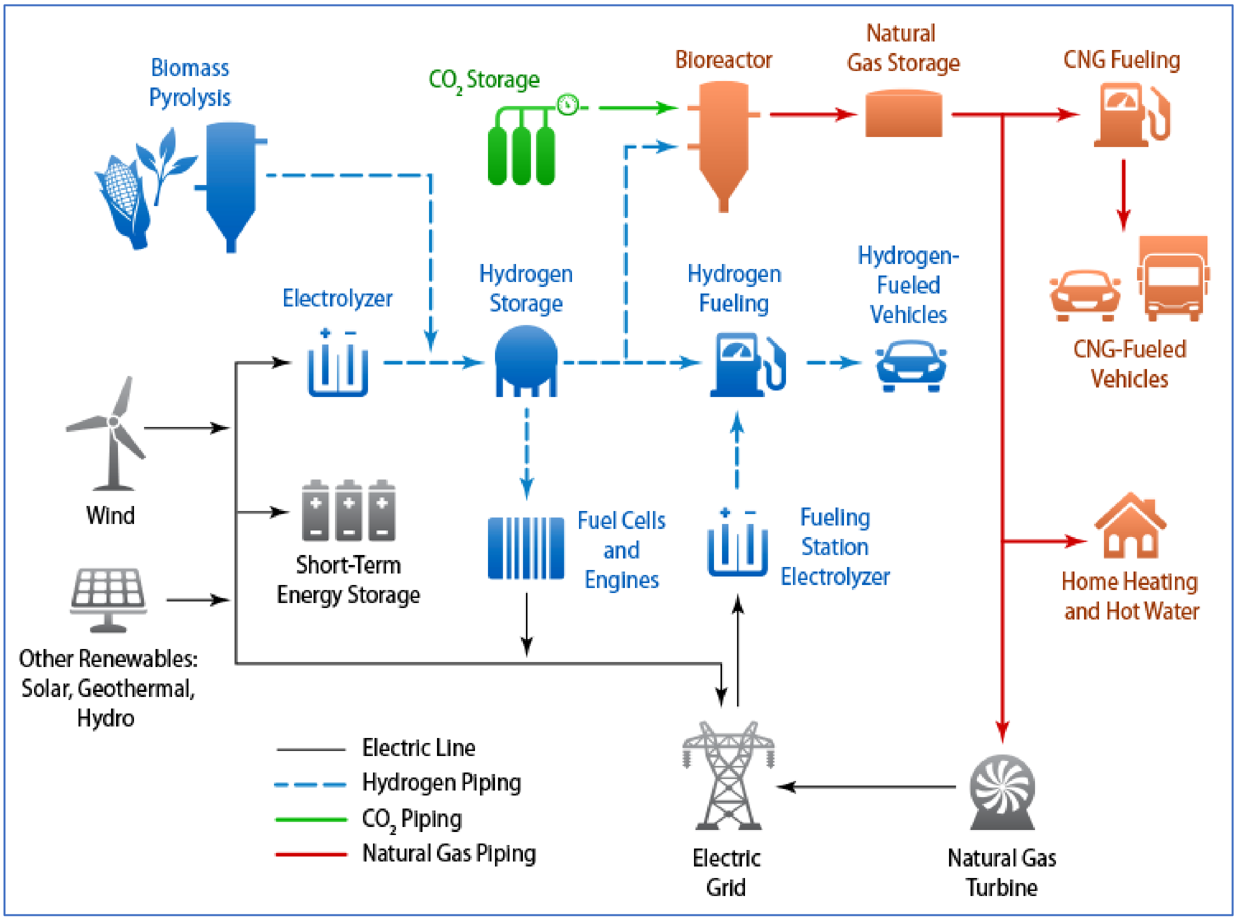


Figure 6 Potential uses for hydrogen in the modern energy economy (U.S. Department of Energy, n.d.)

Several potentially applications of hydrogen seem challenging however. Hydrogen is penalized by its poor round efficiency when it is used for load shifting and electricity generation. . With every year of blockbuster growth in passenger battery-electric vehicles, it appears less likely that hydrogen light-duty FCEVs can compete with the infrastructure and social momentum needed to overtake battery EV adoption to become the Zero-Emission Vehicle (ZEV) of choice. Instead, FCEV's are increasingly confined to the medium-heavy duty transportation market where the economics and physics work more to the advantage of hydrogen. (International Energy Agency, 2015)

A description of the key sources of pipeline hydrogen demand are below:

METHANATION – RENEWABLE NATURAL GAS

Pathway: H_2 Generation → H_2 Methanated into Synthetic CH_4 → Synthetic Methane Injected into Natural Gas Pipelines
Relies on: Electrolysis, Methanation Reactor, Carbon Capture

Converting hydrogen into methane before injection into the natural gas pipeline system is one of the most obvious and immediately accessible ways to safely take advantage of power-to-gas today. This has been an appealing concept, since the natural gas pipeline network(s) can be used as a storage mechanism by taking different forms of renewable energy (e.g. wind) and transforming that into the form of compressed gas in the pipeline (Robb, 2016). Advocates for power-to-gas point out that if hydrogen can be generated with renewable energy, then converted to net-zero GHG methane, it can be stored in the gas pipeline system in large enough amounts to compensate for seasonal shifts in renewable energy production. That renewable methane can also be used flexibly in gas peaker plants, providing grid services needed to compensate for higher concentrations of renewable energy on the grid. (PG&E R&D and Innovation, 2018)

There are several notable advantages to this system. While throughput is constrained by the pace of electrolysis, the total capacity of the gas pipeline system to act as a storage facility for net-zero methane already exist and is large enough to support seasonal shifting. Additionally, there are no gas quality limitations on the amount of blending into the natural gas system (as there would be blending pure hydrogen), since synthetic methane is chemically identical to the methane in natural gas and can be safely injected into a pipeline system optimized for safe delivery and use. Additionally, in order to methanate hydrogen, there is a carbon capture step that uses CO_2 to generate the carbon in methane effectively sequestering CO_2 until the methane is burned or emitted. *For a technical overview of methanation, please see the PG&E R&D Whitepaper on Conversion* (PG&E R&D and Innovation, 2018)*, and the PG&E Technical Analysis on Methanation* (PG&E R&D and Innovation, 2018)*. For an overview of carbon capture and sequestration, please see the PG&E R&D Whitepaper on Alternative Carbon Markets* (PG&E R&D and Innovation, 2018).

In summary, this is viable solution to a key grid challenge (seasonal storage), and a key goal for the gas system (low-carbon fuels and GHG reduction). It will compete with other storage technologies such as batteries, compressed gas and water pumping as well as bi-methane and Renewable Natural Gas generation which can also provide a flexible source of fuel. The economics will pick the winners

HYDROGEN COMMERCIAL AND RESIDENTIAL APPLIANCES

If instead of being injected as methane, some hydrogen is allowed to blend into the system, a major immediate safety concern would be the impact of that hydrogen on customer and commercial appliances. Given the challenge/inertia of requiring changes to end-use appliances, any changes would likely be introduced slowly as the blend percentage of hydrogen increased and as changes become necessary. Even so, adoption of new appliances would likely be phased in over a very long period of time given the low rate of appliance turnover (10-25 years) (deLaski, et al., 2016). This is likely to be the greatest practical restriction on adopting high concentrations of hydrogen (at least 30% per HYREADY) in the gas pipeline.

DOWNSTREAM EXTRACTION OF HYDROGEN

Gas Separation refers to the separation of blended hydrogen and methane that is mixed together in gas pipelines and not the generation of hydrogen from methane (Melaina, 2013). This is an especially important step for applications that demand pure hydrogen: mainly fuel cells for transportation.

While most studies for gas separation have been conducted at small scale, and usually look at relatively low blends of hydrogen and methane (20% hydrogen by volume), some issues have already emerged as a barrier to this process. Current gas separation systems are usually based on the mature *Pressure Swing Adsorption (PSA) system* (Melaina, 2013), described in more detail in the *PG&E Upgrading Whitepaper Analysis* (PG&E R&D and Innovation, 2018). PSA works by increasing and decreasing the pressure of the gas in a column filled with a porous, adsorbent material that preferentially adsorbs certain gases and not others to attain higher purities of a selected gas. In order to achieve a high enough purity of hydrogen, PSA systems would require several columns per location (to conduct the PSA process several times in a row, such as the photo on the right), with significant pressure increases and drops. Each additional bed adds significant capital cost, and the intensity of the pressure swings also adds significant variable cost and consumption of energy.

Figure 7 Industrial Pressure Swing Adsorption Plant (AIChE, 2014)

Gas separation is *not* cheap in both energy and money. Some estimate that every $1/kg is equivalent to $1 of gas, separation can add between $2-9 (Ogden, 2018). In some cases, it may be cheaper to run a dedicated hydrogen pipeline between the source of hydrogen and the destination or to produce hydrogen locally..

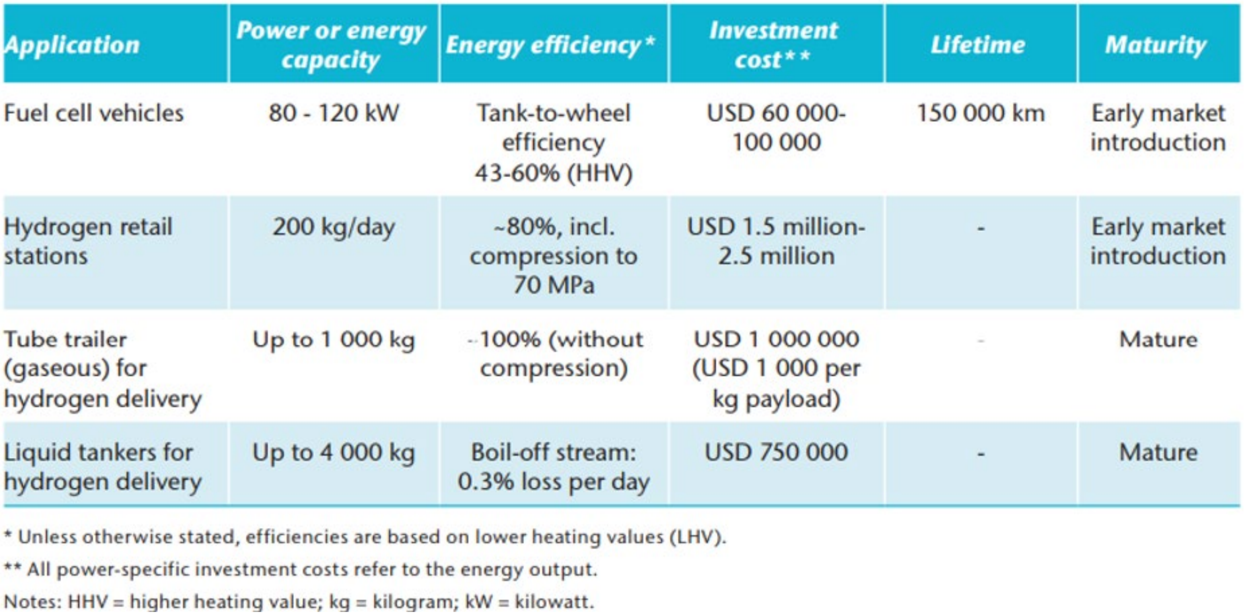
Some technology alternatives such as *membrane separation*, are currently explored to improve efficiency and lower cost but it is unclear whether or not the technology could be used at scale. Please see the *PG&E Upgrading Whitepaper Analysis* (PG&E R&D and Innovation, 2018). Some have also suggested a hybrid system of combination reactors and membrane separation, and electrochemical separation but most studies still remain in early stages. (Melaina, 2013)

COMPRESSION/SUPPORTING INFRASTRUCTURE FOR HYDROGEN FUELING STATIONS

Because much of hydrogen application requires compression (i.e. as stored fuel in hydrogen fuel cell vehicles, or in storage), compression is an important step. Even within the pipeline, Hydrogen has a significantly lower energy density by volume than methane (by a factor of 3) so for the same concentration of molecules, hydrogen offers 3x *less* energy than traditional natural gas. However, on a weight basis, Hydrogen has a higher energy density than methane. (UK Hydrogen and Fuel Cell Industry, 2011)

To compensate, some argue that the hydrogen can be compressed to offer greater density. However, at higher concentrations of hydrogen, this approach runs up against the inflexibility of MAOP, or maximum allowable operating pressure, that is a safety constraint designed to keep pressure stresses on pipelines within safe limits. This limits the practical amount of energy hydrogen that can be blended into the system, or reduces the amount of energy that system can hold congruent with how much hydrogen is blended w natural gas. For example, A mix of hydrogen (10%) and methane (90%) by volume results in a 5–6 % decrease of the transport capacity of pure methane alone (Lehner, 2014).

Table 2 Current Performance of Hydrogen Systems in the Transport Sector (International Energy Agency, 2015)



Application	*Power or energy capacity*	*Energy efficiency**	*Investment cost***	*Lifetime*	*Maturity*
Fuel cell vehicles	80 - 120 kW	Tank-to-wheel efficiency 43-60% (HHV)	USD 60 000-100 000	150 000 km	Early market introduction
Hydrogen retail stations	200 kg/day	~80%, incl. compression to 70 MPa	USD 1.5 million-2.5 million	-	Early market introduction
Tube trailer (gaseous) for hydrogen delivery	Up to 1 000 kg	~100% (without compression)	USD 1 000 000 (USD 1 000 per kg payload)	-	Mature
Liquid tankers for hydrogen delivery	Up to 4 000 kg	Boil-off stream: 0.3% loss per day	USD 750 000	-	Mature

* Unless otherwise stated, efficiencies are based on lower heating values (LHV).
** All power-specific investment costs refer to the energy output.
Notes: HHV = higher heating value; kg = kilogram; kW = kilowatt.

HYDROGEN FUEL CELLS AND FUEL CELL VEHICLES

Hydrogen Fuel Cells are designed to produce electricity from Hydrogen, and are most commonly used for transportation.

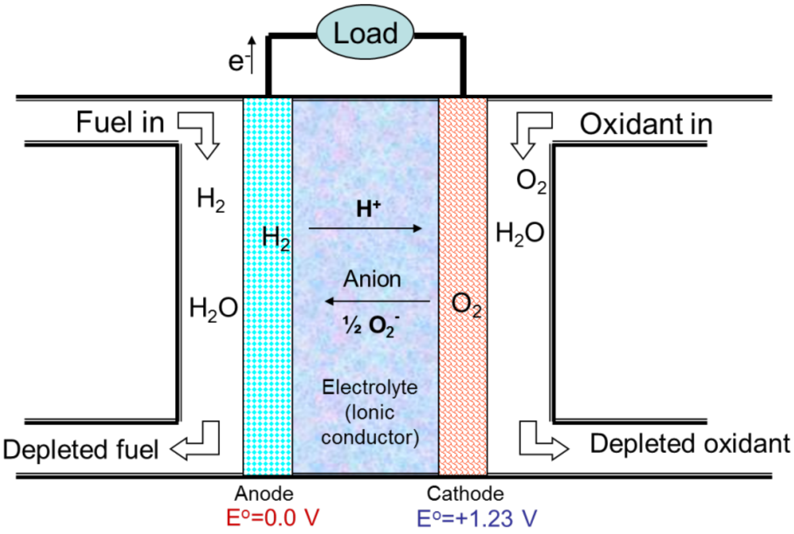


Figure 8 Principle of Fuel Cells (LIu, 2000)

Since Producing electricity, storing it as hydrogen, and then reproducing it through a fuel cell has a very low round-trip efficiency (you only end up with 40% of the electricity you started out with), the most practical application for hydrogen fuel cells is in light, medium, and heavy vehicles (Fuel Cell Technologies Office, 2015). Even with the emerging dominance of battery electric vehicles (BEVs) in the personal cars, Hydrogen FCEVs can scale well to large power, are very light in weight, produces both heat and electricity, and can be refueled rapidly making them ideal for medium- to heavy-duty vehicle applications as well. (DriveClean, 2018)

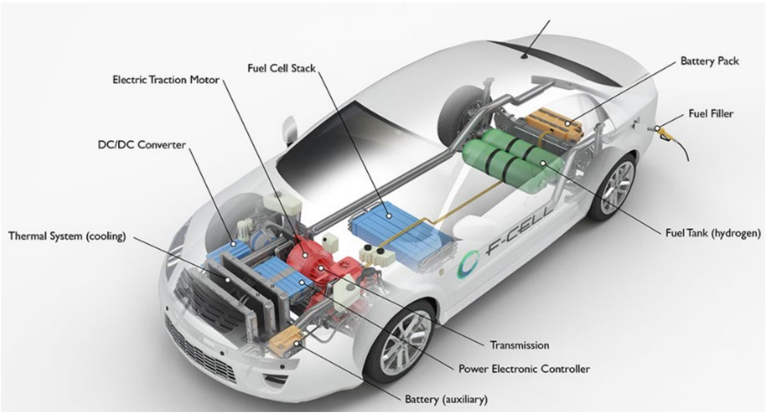


Figure 9 Hydrogen Fuel Cell Vehicle (U.S. Department of Energy, 2018)

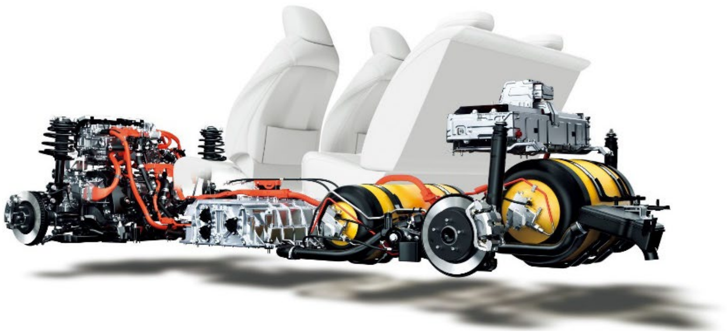


Figure 10 Hydrogen Fuel Vehicle Powertrain Prototype (Toyota, 2018)

Real World Example – Heavy Duty Hydrogen Fuel Cell Electric Truck
Toyota Class 8 Drayage Truck – Project Portal Demonstration Project
Southern California, 2017
The Toyota Class 8 Drayage Truck is one of the first heavy-duty hydrogen fuel cell electric trucks to be made for commercial availability in the United States. It is being tested at Toyota's facility in Arizona for operating cost and reliability data for comparison against diesel and potentially new battery-electric medium- to heavy-vehicle alternatives. The project, called "Project Portal" began in October 2017 and will run for an undefined period. (O'Dell, 2017)

More Hydrogen Medium- to Heavy-Duty Hydrogen FCEV Concepts and Pilot Projects:

More on the Toyota Heavy-Duty Fuel Cell Truck: Toyota's Heavy-Duty Fuel Cell Truck Finally Hits the Road
GM's Heavy-Duty Hydrogen Truck concept: General Motors Teases Heavy-Duty Hydrogen Fuel Cell Truck
UPS Operationalizes Hydrogen Fleet: UPS Launching World's First Fuel Cell Electric Class 6 Delivery Truck

Macro Challenges (High Level):

Hydrogen is a brave new world. While it offers a great deal of promise, it also comes with a great deal of risk, associated with the lack of knowledge and experience around hydrogen injection into natural gas pipelines. Much of the "facts" used to justify arguments for or against hydrogen in utility pipelines are based primarily on theoretical assumptions, because very few projects of this type operate worldwide, and nearly all are extremely recent demonstration projects. However, here are some of the key challenges that utilities can widely anticipate needing to address before establishing injection projects for hydrogen.

- **Hydrogen Embrittlement and Corrosion** – Hydrogen has an active electron, and can easily migrate into the crystal structure of most metals. Therefore, steel pipes – particularly the steel welds – used for transmission pipeline infrastructure can suffer from embrittlement and cracking after continuous exposure to hydrogen. Any pipe transporting hydrogen (or any metal exposed to it) must be resistant to corrosion or cracking.
- **Needed Monitoring and Measurement Tools for Hydrogen** – Most hydrogen is transported today in dedicated Hydrogen pipelines, and natural gas pipelines have not needed to be retrofitted to

accommodate the needs of hydrogen. Using utility pipeline systems implies the need for certain types of safety features that either do not exist or are as yet undeveloped. There is need for a hydrogen odorant (none exist at present). Utilities need leak detection and monitoring devices that are either specifically designed for hydrogen or can detect both hydrogen and methane.

- **Efficiency of Hydrogen Generation or Separation** – While Hydrogen is theoretically an excellent form of renewable energy storage, physical and chemical realities mean that any P2G option is extremely inefficient. The conversion of electricity to gas is itself an entropic process. While 70% efficiency (Wikiwand Power-to-Gas, 2018) for electrolysis is comparable to the round-trip efficiency of lithium-ion batteries, hydrogen can only be used when burned, or when methanated into natural gas, both of which further degrade the efficiency of hydrogen use.
  Specifically: Generating Hydrogen from renewable energy through electrolysis is 70% efficient. Converting it to methane reduces the efficiency even further to around 54%. If burned, the energy generated could be even 50% less than that (25% of the original electricity). If used in a fuel cell it could have a slightly better efficiency of 60%, for about 30% of the total electricity. (International Energy Agency, 2015) Are there alternative methods that offer better efficiencies? Is there a clever way to produce and use hydrogen that allows us to circumvent these rules? (Wikiwand Power-to-Gas, 2018)
- **Current Appliances were Designed for Methane, not Hydrogen** – End-use appliances for residential customers (and to an extent, commercial customers) were designed around the chemical properties of methane, not hydrogen. How will hydrogen blending impact the safe use or lifecycle of appliances?
- **Hydrogen Market Development Path is Risky** – Hydrogen has a great deal of potential, but much of it rests on infrastructure development that does not yet exist – hydrogen-tolerant pipeline networks, hydrogen refueling infrastructure, hydrogen generation facilities, etc. Taking fuel cell EVs as an example, it is estimated that it could cost $900-$1,900 of investment per FCEV to develop necessary support structures until 2050 (Starling, 2015). This challenge falls into the chicken-and-egg paradigm, where few wish to make these sizeable investments in infrastructure required to support the market without seeing growth, and in turn, the market does not grow without the supporting infrastructure. Being the first to make these investments is a significant risk, without sure uptake of demand for hydrogen products after that investment has been made. Few companies have the capacity to make this kind of high volume, expensive, up-front, high risk investments. Instead, coalitions such as the Hydrogen Council have been forming around Hydrogen suppliers to reduce the risk of going-it-alone, but they have yet to see significant progress at this time.
- **Much is Unknown** – While Hydrogen is generated in significant amounts in the US, there are a vanishingly small number of projects that have injected hydrogen into the gas pipeline system throughout the world (only 1 so far in the United States), and all those have come in the last few years. Few demonstration projects are running in Europe such as P2G Ibbenbüren and WindGas Falkenhagen in Germany, HyDeploy in the UK and Juniper in France. (Navas, 2017)There is a striking need to develop engineering, safety, and gas quality standards around Hydrogen that simply do not exist yet. PG&E has partnered with organizations around the world on the HYREADY Project to begin determining these standards. Until projects like HYREADY are completed, many challenges associated with delivering hydrogen may fall into the “unknown unknowns” category.

The Future of Technology

Successful technologies or processes will address the following:

1. Get around the inefficiency of generating or converting electricity to hydrogen, or hydrogen to methane or vice versa.
2. Provide infrastructure for natural gas pipelines that is also resistant to H_2 embrittlement.
3. Monitor, measure, or offer integrity management tools for Hydrogen, specifically.
4. Develop products that fill out the downstream market demand for hydrogen in a safe and flexible way (i.e. appliances that can handle hydrogen as well as gas, H_2 fuel cell cars).
5. Identify a cheaper method or a new method of separating methane and hydrogen from the blended pipeline gas.

Potential R&D Projects for Pipeline Hydrogen

While PG&E may develop alternatives to hydrogen pipeline injection before such a step is needed, with current technologies, it seems likely that PG&E will need to generate at least some hydrogen for the gas system to meet long-term 2050 goals for GHG reduction mandated by the State of California. The following are the categories of technologies that are priorities for PG&E in addressing some of the key challenges for adoption and usage of hydrogen as storage, as a source of synthetic natural gas, for residential gas delivery, or as a transportation fuel in California. The Gas R&D and Innovation team can expect partnership and support from the Clean Transportation team in funding and developing projects associated with hydrogen as a transportation fuel.

1. MORE EFFICIENT FORMS OR USES FOR POWER-TO-GAS/HYDROGEN AS A CATALYST

Even in the best of circumstances, the efficiency of generating hydrogen from electricity through to its point of use to produce electricity or mechanical work is limited by thermodynamics. However, that's only if hydrogen is used for its energy content. If instead, hydrogen is used as a catalyst in a process to generate renewable natural gas, it may make the RNG generation process cleaner, and offer higher energy efficiency.

Current PG&E Gas R&D Project: G4 Insights

The G4 PyroCatalytic Hydrogenation (PCH) process is a thermochemical process that enables large scale, economic production of renewable natural gas (RNG) from lignocellulosic biomass and hydrogen gas. G4 PCH process is not gasification and methanation. The G4 technology is unique because the process is realized in a single catalytic conversion stage that does not entail intermediate production of syngas prior to methanation. G4 combines fast pyrolysis, catalysts and a hydrogen atmosphere to preferentially convert gas directly to methane. Hydrogen gas that is produced using excess renewable electricity is converted into methane and stored in the gas system. Leveraging the ATCO Gas pilot in Alberta, Canada, R&D and Innovation plan to evaluate G4 Insights technology's ability to produce RNG from H_2 and woody biomass.

2. HYDROGEN ENGINEERING AND BLENDING STANDARDS

At the moment, our understanding of how hydrogen impacts the natural gas pipeline system when injected is limited, because despite advancements in renewable fuels around the world, few have injected hydrogen into natural gas pipelines. However, before hydrogen can safely be interconnected, its impact on the gas pipeline system, its components, the critical interconnection equipment, and impacts on end-use appliances must be understood better.

Current PG&E Gas R&D Project: HYREADY
HYREADY is a joint industry project (JIP) between companies in the US, Canada and Europe to prepare clear engineering guidelines for transmission and distribution system operators to support the preparation of existing natural networks and operations for the injection of H_2 (pure and as a gas component) up to a 30% blend, with acceptable consequences. The engineering guidelines will allow utilities to assess their system end-to-end to determine if existing infrastructure is safe for H_2 injection, and if not, provide recommendations on what steps to take to make the system H_2 tolerant.

3. HYDROGEN GAS SEPARATION

No matter how much hydrogen blending the pipeline can tolerate, the cost and technical feasibility of separating hydrogen from methane at the point of demand is a critical technical bottleneck. Currently, compression needs for PSA make the process uneconomic at large scale, and other alternatives, such as membranes, do not scale easily. Identifying a cheap, alternative method for gas separation is a key hurdle before the hydrogen value chain can be fully realized.

Who are Experts in this field?

Experts on various aspects of the (pipeline) Hydrogen value chain:

Table 3 Individual and Technology Specific Experts

Industry Experts	Expert	Alternative
California	**PG&E Clean Transportation Team**: Gracie Brown, Principal UC Irvine Professor Jack Brouwer, **UC Davis Institute of Transportation Studies:** Dr. Joan Ogden Dr. Marshall Miller	PG&E Fleet
United States		Hawaii Gas
International	International Partnership for Hydrogen and Fuel Cells in the Economy	
Technologies		
Hydrogen Light Duty Vehicles	Toyota Motors	The Japan Hydrogen & Fuel Cell Demonstration Project
Hydrogen Med/Heavy Duty Vehicles	Toyota Motors	
Hydrogen Fuel Cells	**Fuel Cell and Hydrogen Energy Association:** Morry Markowitz	

Power-to-Gas	**NREL** Josh Eichman Francisco Flores-Espino MW Melaina O. Antonia M. Penev	**Stanford** Albert Spormann **Opus 12**
Hydrogen Generation – Electrolysis, etc.	**Office of Energy Efficiency and Renewable Energy, Fuel Cell Technologies Office:** Jamie Holladay Cecelia Cropley	**Gas Technology Institute (GTI)** Dr. G. (Subbu) Subbaraman
Pipeline Infrastructure Hydrogen Safety (including end-use, compressor, storage)	HYREADY Project NYSEARCH RANGE™ Tool Enhancement Project Carlos Navas	GTI H_2 Embrittlement Study
LCFS Credits	**PG&E Internal SME's:** Mukul Shakur	
Federal Rin Credits	**Environmental Protection Agency (Congressional Budget Office):** Terry Dinan Ron Gecan David Austin	

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