Hydrogen: Hype or a Glide Path to Decarbonizing Natural Gas—Part 2

Thomas N. Russo

As discussed in Part 1 of this series, hydrogen (H_2) is being debated across the globe as a means of reducing greenhouse gas (GHG) emissions, specifically in efforts to decarbonize the existing energy and transportation sectors. In these discussions, stakeholders use multiple terms such as hydrogen-enriched natural gas power (HENG),[1] power-to-gas (P2G), green H_2, and renewable H_2. All of these terms generally mean producing H_2 with excess renewable power using electrolyzers, which appears to be the preferred policy option.[2] For the purposes of this article, green H_2 will be used and to distinguish it from blue H_2, which can use natural gas as a feedstock with steam methane reforming.

Using the existing natural gas grid[3] to transport H_2 rather than building a separate system makes a great deal of sense. As a result, H_2 would decarbonize the natural gas industry as well as a large part of the power, heating, and industrial sectors. Such a transition would strengthen the use of H_2 fuel-cell electric vehicles (FCEVs) that are competing with battery-electric vehicles (BEVs) used in passenger vehicles and heavy trucks.

H_2 would decarbonize the natural gas industry as well as a large part of the power, heating, and industrial sectors.

However, as this author stated in Part 1 of this series, H_2 production needs to ramp up significantly above its current level of 117 metric tons (Mt) produced in 2018 to serve these sectors, and especially to supply FCEVs. Refineries and ammonia plants used 59 percent of the H_2, while methanol plants, steel fabrication, and heating used the remaining 41 percent. Only 0.01 Mt of H_2 was used by the transportation sector in 2018.[4] This author also recommended that governments need to step up and use tax incentives over the next 20 years to encourage production of blue H_2 with Carbon Capture Utilization and Storage (CCUS) and green H_2 using renewable power and electrolyzers. If government policies in these areas are not robust, then H_2 will not be a significant player in the energy transition. For this article, the author will focus on:

[1] National Grid and Atlantic Hydrogen Inc. (2009). *Hydrogen-enriched natural gas—Bridge to an ultra-low carbon world.* Retrieved from https://www.osti.gov/etdeweb/servlets/purl/21396875.

[2] There are also discussions in the United States about using nuclear power and electrolyzers to produce green H_2.

[3] The natural gas grid includes the transmission and distribution pipelines.

[4] International Energy Agency. (2019). *The future of hydrogen.* Paris: Author. Retrieved from https://www.iea.org/reports/the-future-of-hydrogen.

Thomas N. Russo has over 30 years of experience in energy regulation, infrastructure, markets, environmental impact assessment, and energy security. Prior to starting Russo on Energy LLC, he worked for over 30 years as a manager and senior energy industry analyst at the Federal Energy Regulatory Commission. He also is an adjunct professor in the Elliott School of International Affairs at The George Washington University in Washington, DC, where he teaches courses in global energy and international energy and environmental regulations.

 © 2020 Wiley Periodicals LLC / DOI 10.1002/gas.22187

- The status of efforts to blend H_2 in the US gas grid
- What H_2 blending means for decarbonizing natural gas
- Regional opportunities to increase H_2 in the United States and serve FCEVs
- The disconnect between H_2 policy and green H_2 production shortages

BLENDING H_2 WITH NATURAL GAS

The concept of using the natural gas grid to transport H_2 is not novel. Comprehensive studies such as the 2013 National Renewable Laboratory (NREL) report on H_2 blending and generation[5] provide a sound basic overview of the issues. The NREL report relies heavily on research conducted by the Gas Technology Institute (GTI), which is still actively involved in research.[6] Natural gas utilities' trade associations have been partnering with universities, research laboratories, and the GTI to conduct needed research and development (R&D) on the effects of blending H_2 in natural gas pipelines and distribution lines (**Table 1**).

However, the percentage of H_2 that can be blended safely with natural gas in pipelines and distribution systems is still an open question challenging the industry. These challenges include:

- Maintaining the integrity of pipeline and distribution lines
- Managing potential gas leakage
- Identifying potential adverse impacts on material durability
- Determining if safety can be maintained
- Assessing whether equipment used by end-users will work properly

Six countries have been actively running tests on blending various percentages of H_2 in the gas grid and interest is also growing in P2G projects, especially in Europe. Germany, and Australia have had the most H_2 blending projects, but France, the United Kingdom, Italy, and

[5] Melaina, M. W. (2013). *Blending hydrogen into natural gas pipeline networks: A review of key issues.* Golden, CO: National Renewable Energy Laboratory. Retrieved from https://www.nrel.gov/docs/fy13osti/51995.pdf.

[6] Weeks, B. (2020). *Presentation on H2 blending and generation.* Des Plaines, IL: Gas Technology Institute.

Table 1. Research Reports on Blending Hydrogen in Natural Gas Grids

Partner	Scope
AGA/CGA:	Blending of Hydrogen into Natural Gas Delivery Systems (2018)
Gas Technology Institute:	Hydrogen Blending into the Natural Gas Network – A Risk Analysis (2010)
	Initial Assessment of the Effects of Hydrogen Blending in Natural Gas on Properties and Operational Safety (2015)
HYREADY:	Engineering Guidelines – For the preparation of natural gas systems for hydrogen / NG mixtures (2018)
University of California, Irvine:	Pilot project for power-to-gas with solar PV
DNV-GL:	Mathematical demonstration of the amount of hydrogen that can be added to natural gas (2017)
University of Southern California:	Hydrogen Embrittlement Literature Review (2014)
	Permeability and Porosity Measurements of Gas Storage Rock Samples (2010)
University of Illinois at Urbana-Champaign:	Evaluating Hydrogen Embrittlement of Pipeline Steels (2016)
Sandia National Laboratories:	Hydrogen Effects on Materials for CNG / H2 Blends (2010)
Colorado State University:	Impact of H2-NG Blending on Lambda Sensor NSCR Control and Lean Burn Emissions (2015)
NYSEARCH RANGE™	Interchangeability study for hydrogen-natural gas blends on SoCalGas customer equipment.

 DOI 10.1002/gas /

Table 2. Selected Global Hydrogen Blending Projects

Project Sponsor	Hydrogen Blend Levels
ENGIE GRHYD (France)	10% (will be increased to 20% this year or in 2020) in a new residential area of 100 homes and health center boiler; 2-year demo started in 2018
ITM Power HyDeploy (UK)	0 – 20%; 12-month Trial - Summer 2019; *Since 1993, EU legislation, all new gas appliances are performance and safety tested with methane blended with 23% hydrogen
Energiepark Mainz (Germany)	0 -15% at 6 - 8 bar (87 - 116 psi); mixing occurs in a stub line; Started 2015
H2V Product (France)	0 – 6%; Industrial program for development, construction and operation of hydrogen plants to inject into gas pipelines; Planned, not started
Snam (Italy)	5%; gas transmission network, feeding two industrial customers (pasta factory and water bottling company); April 2019 for one-month test
P2G NFCRC Phase 2 @ UCI (USA)	0 – 3.4%; 4" iron pipe with gas turbine at 21- 28 bar (304 – 406 psig); Started 2016
ITM Power/Mainova/NRM Thuga plant (Germany)	< 2% at 3.5 bar (50 psi) with no compressor used for injection; Started in 2013
Wind to Gas Brunsbüttel (Germany)	0 – 2%; Started March 2019; *DI standard currently limits the hydrogen content in natural gas to a maximum of 2%, if a natural gas filling station is located nearby
RH2-PtG (Germany)	0 - 2% at 25 bar (362 psi); max permitted concentration is 2%; Planned, not started
Australian Gas Infrastructure Group (AGIG) Hydrogen Park SA (Australia)	Australia's first integrated hydrogen-electricity-gas project; Planned mid-2020
Jupiter 1000 (France)	First industrial demonstrator of Power to Gas with a power rating of 1 MWe for electrolysis and a methanation process with carbon capture; 200 m3/h hydrogen injection; start-up in 2018
Hydrogen Injection in Sydney (Australia)	As part of the trial, a portion of hydrogen produced will be diverted to a gas engine generator to generate electricity generation to be exported back into the grid, with the remaining stored for use in an onsite refuelling station for hydrogen fuel cell vehicles
ATCO Hydrogen Microgrid (Australia)	"Green hydrogen" from on-site solar using electrolysis, fueling a range of gas appliances and blending hydrogen into the natural gas pipeline; Planned 2019

Source: Modified from SoCal Gas, Southwest Gas, and PG&E presentation before California PUC, March 2019.

the United States are also working in this area (**Table 2**).

California is a leader in deploying H_2 in its energy transition, and most experts hope that 20 percent of the state's energy needs will come from the fuel.

California is a leader in deploying H_2 in their energy transition, and most experts hope that 20 percent of the state's energy needs will come from the fuel.[7] The California Energy Commission (CEC) has budgeted $20 million per year to fund 100 light-duty H_2 fueling stations by 2024 and 200 stations by 2025 for use in FCEVs.[8] As of March 24, 2019, 64 fueling stations were funded and 46 were operating. The CEC also spends $25 million annually on natural gas R&D and $100 million on electricity R&D. The CEC and the California Public Utility Commission (California PUC) are also developing tariffs and policies for interconnection and injection of renewable hydrogen in the state's natural gas grid, including efforts to blend H_2 into the gas grid to distribute it throughout the state.

The German Gas and Water Association[9] and Pacific Gas & Electric (PG&E)[10] examined the

[7] Reed, J. (2019, March 24). *Society needs hydrogen and fuel cells.* California Public Utility Commission Workshop. Retrieved from http://www.adminmonitor.com/ca/cpuc/workshop/20190524/.

[8] California Public Utility Commission, March 24, 2019, hearing and presentation by California Air Resources Board.

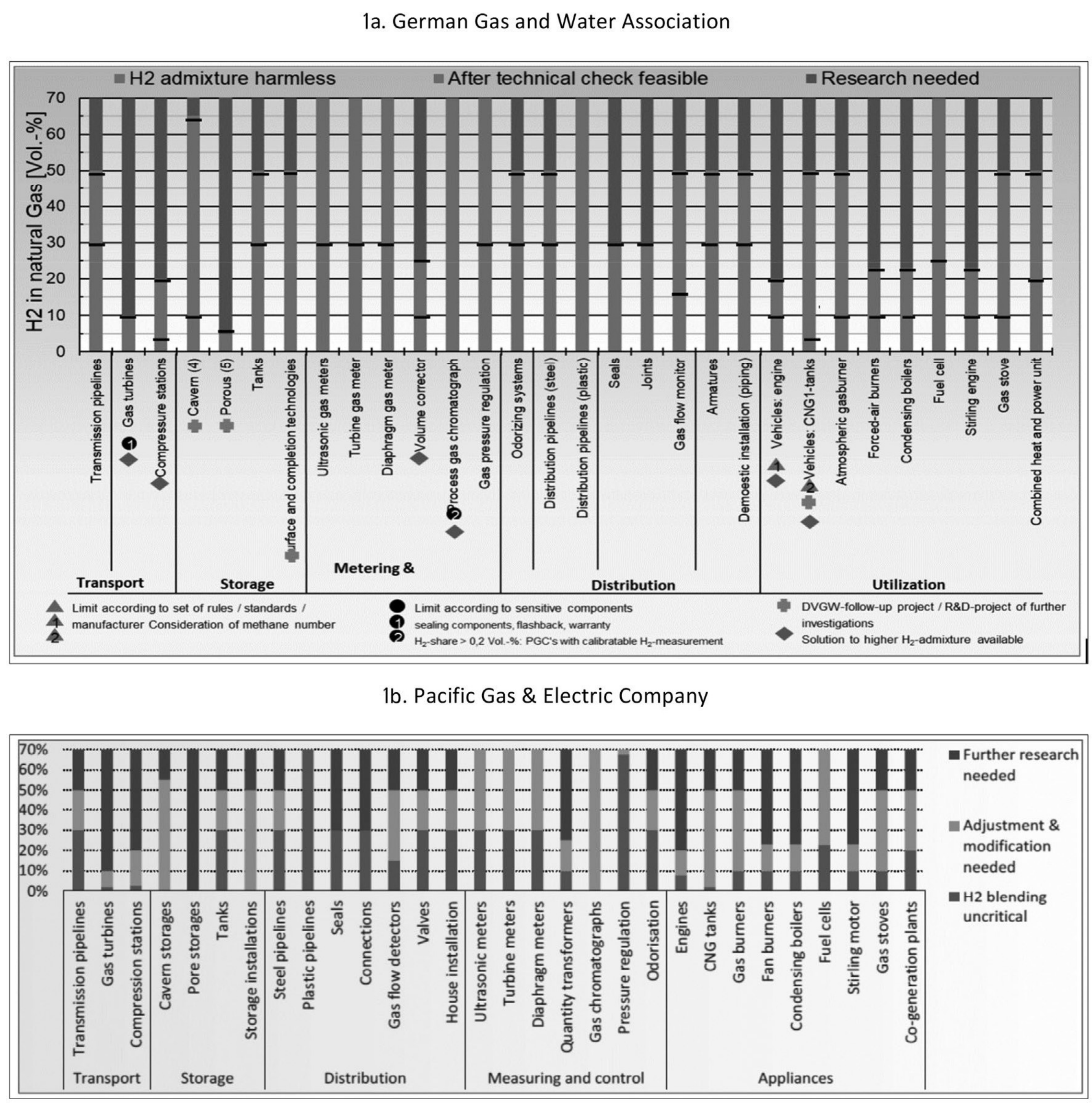
[9] Linke, G. (2018, December 7). *Hydrogen integration in natural gas grids: Quantitative assessment of its carbon footprint, technical feasibility and economic rationale.* Presented at WS2 GAC meeting, Brussels, Belgium.

[10] PG&E Gas R&D and Innovation. (2018, September 18). *Pipeline hydrogen.* Retrieved from https://www.pge.com/pge_global/common/pdfs/for-our-business-partners/interconnection-renewables/interconnections-renewables/Whitepaper_Pipeline-HydrogenAnalysis.pdf.

effects of blending various percentages of H_2 in their gas grids. For steel natural gas transmission and distribution lines, blends up to 30 percent H_2 were acceptable (**Figure 1**). Both studies show that plastic distribution lines could accept blends up to 70 percent. The higher percentage of H_2 is likely because the majority of distribution lines operate at lower pressure than gas transmission lines and are made of polyethylene instead of steel. Steel natural gas transmission lines are subject to embrittlement from the H_2. While encouraging, other components of gas transport, storage, distribution, metering and control, and use/appliances require further research to determine the risks of exposure to blended H_2 injections.

Given these results, it should be no surprise that regulators have established legal limits or regulatory blend walls in many countries and states to limit H_2 blending in natural gas grids (**Figure 2**). These limitations or barriers may

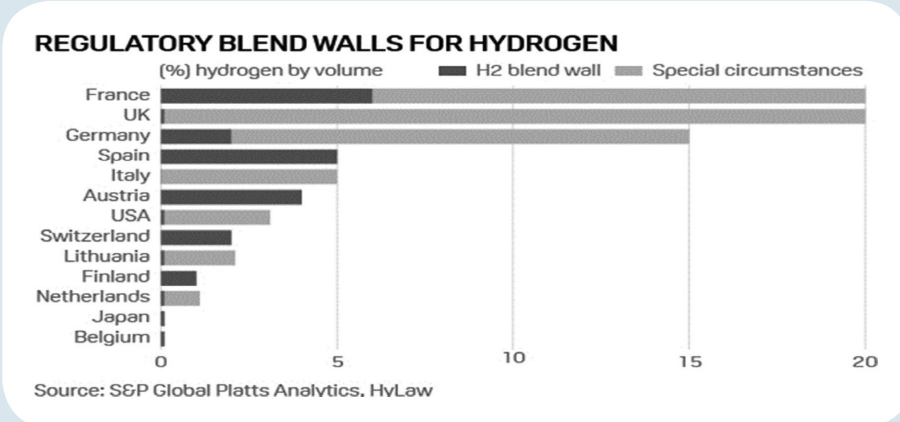
Figure 1. German and California Gas Utility H2 Blending Study Results



Source: German Gas and Water Association and PG&E, 2018.

DOI 10.1002/gas / © 2020 Wiley Periodicals LLC

Figure 2. Legal and Regulatory Barriers to H2 Blending in Gas Grids by Country



thwart efforts to transport blended H_2 to end-users in the heating, power, and transportation sectors. This also would necessitate the transportation of H_2 via truck, rail, and existing H_2 pipelines.

While these studies shed some light on the effects of H_2 blending in gas grids, individual pipeline companies and natural gas utilities along with regulators in Europe, the United States, and Australia may be reluctant to use H_2 blended fuels. According to Europe's Hydrogen Law,[11] the legal framework in the European Union regarding acceptable H_2 levels that can be blended in gas grids does not exist. Even in Germany, where injection of H_2 is permitted, there is a diversity of arrangements on whether 100 percent H_2 must be blended down to the acceptable gas quality/composition prior to injection into the gas grid. Natural gas pipeline companies and gas utilities in Europe and in states like California that wish to decarbonize their energy sector using H_2 must resolve the following issues before going forward, otherwise the use of the fuel will depend on transportation by truck, tanker, or rail:

- Configure and design pilot studies of gas grid H_2 blending levels consistently so results can be used to define a wider and safer basis for adoption across a region, state, or country.
- Develop nondiscriminatory interconnection fees and tariffs.
- Develop standards for the manufacturing of gas pipeline valves, metering, and detection that work with H_2 blended gas.
- Develop standards that include pricing H_2 blended natural gas at the wholesale and retail level.
- Develop or amend gas grid H_2 blending levels to match energy-sector decarbonization goals.

CALIFORNIA AND HYDROGEN BLENDING

The California PUC is very interested in blending H_2 into the California gas grid and held a public workshop on hydrogen on March 24, 2019. Experts from natural gas utilities SoCal Gas, PG&E, and Southwest Gas, as well as experts from the California Air Resources Board (CARB), the University of California, Irvine's National Fuel Cell Research Center, Mitsubishi Hitachi Power Systems, Hitachi Zosen Inova, and others participated.[12] A joint presentation by the California gas utility representatives on blending H_2 in the California gas grid highlighted concerns around numerous issues

[11] The Hydrogen Law calls for the removal of legal barriers to the deployment of fuel cells and hydrogen applications.

[12] California Public Utility Commission. (2019, May 24). *Workshops to consider a standard renewable natural gas interconnection tariff and an inquiry into the standards required to inject and interconnect renewable methane and hydrogen projects.* Retrieved from http://www.adminmonitor.com/ca/cpuc/workshop/20190524/.

 © 2020 Wiley Periodicals LLC / DOI 10.1002/gas

resulting from their review of global literature on the topic (**Table 3**).

The California utilities also indicated the need for real-time studies in controlled and isolated parts of their systems to help them understand potential impacts and how they should modify and adapt their systems at the interconnection and injection sites and downstream. The California utilities wish to work jointly with the California PUC in identifying pilot sites, and isolating systems to obtain real-life data on the overall impact to their natural gas systems. In turn, the California PUC asked the utilities for specific recommendations on sites that could be studied.

Despite the ongoing R&D in the United States and abroad, the natural gas industry is still in search of answers regarding H_2 blending in gas grids and their impacts on end-users. The guidance gleaned from the aforementioned studies and directly from manufacturers of gas pipes, valves, engines, turbines, and others is adding to the confusion (**Figure 3**). A natural gas pipeline or gas utility must also consider how H_2 blending will affect the safety and performance of end-users, not just on their own equipment. Gas grids, in general, have common characteristics and elements. However, the composition of pipes, valves, seals, etc. is not standardized other than to perform safely with natural gas. Therefore, determining the percentage blend of H_2 is very important.

Table 3. Concerns of California Natural Gas Utilities Regarding H_2 Blending in the Gas Grid

Area for Near-Term Analysis	Research Topic
System Integrity	Potential embrittlement
	Crack growth
	Permeation
	Interaction with reservoir caprock
	Impact on sealant
End User	Combustion
	Flame sustainability
System and Industrial Equipment	Impact on engines
	Impact on equipment
	Measurement accuracy

Source: SoCal Gas, PG&E, and Southwest Gas presentation.

CO_2 EMISSIONS REDUCTIONS AND H_2 REQUIRED

California's total consumption of natural gas in 2018 was 4,432,552 million cubic feet (MMcf) (**Figure 4**). Despite the growth of renewables and efforts to decarbonize the energy sector, the state consumed two times the amount of gas consumed by Texas in 2018.

Since most natural gas consumers in California are served by the four major gas utilities, this author calculated the quantity of CO_2 equivalent (e) emission reductions[13] that would be achieved by blending H_2 in the state's natural gas grids (**Table 4**). Blending the bare minimum of 5 percent H_2 would achieve a reduction of 12.2 million metric tonnes (Mt) of CO_2, which is a 3 percent reduction in the state's total CO_2 e emissions of 424.1 Mt in 2017.[14] If H_2 blends of 30 percent and 70 percent were achievable without risk to the gas grid, significant reductions of 17 percent to 40 percent in CO_2 e emissions could be realized. In addition, the existing gas grid would be able to actively participate in and play a greater role in the state's clean energy transition. Benefits would also accrue to gas-fired power plants that could burn higher H_2 blends and FCEVs.

According to the International Energy Agency (IEA), there are approximately 3 million kilometers, or 1.9 million miles, of natural gas transmission pipelines and a far greater number of distribution lines that could potentially transport blended H_2. The American Gas Association reports the gas industry operates an extensive system of 2.6 million miles of distribution and transmission pipelines that serve more than 178 million Americans. Of that amount, more than 300,000 miles is composed of natural gas transmission pipelines according to the Interstate Natural Gas Association of America.[15] Therefore, the potential for blending H_2 in these systems is significant, provided the safety and technical concerns in Table 3 can be managed well.

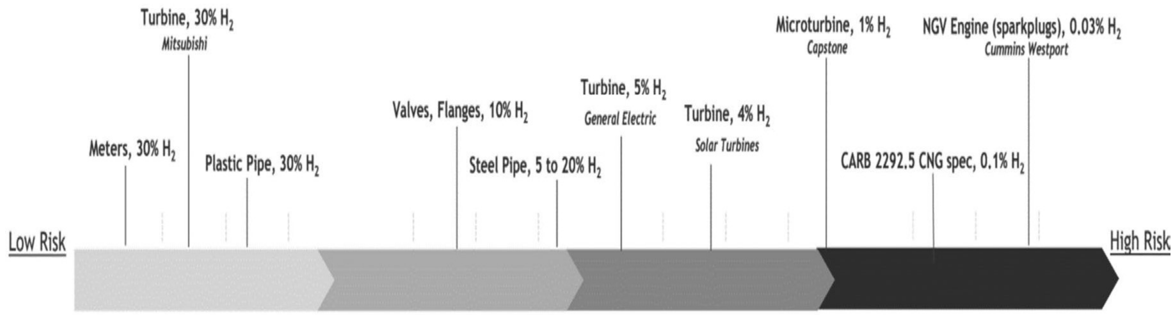
[13] Using the Environmental Protection Agency's Greenhouse Gas Equivalencies Calculator, at https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator.

[14] GHG Current California Emission Inventory Data, at https://ww2.arb.ca.gov/ghg-inventory-data.]

[15] Interstate Natural Gas Association of America, at https://www.ingaa.org/Pipelines101.aspx.

DOI 10.1002/gas / © 2020 Wiley Periodicals LLC

Figure 3. Risks of H2 Blending and Percentage Allowed for Gas Grid and End-Users*



*These risks from various sources are not conclusive for the California gas grid.

Source: SoCal Gas, PG&E, and Southwest Gas presentation.

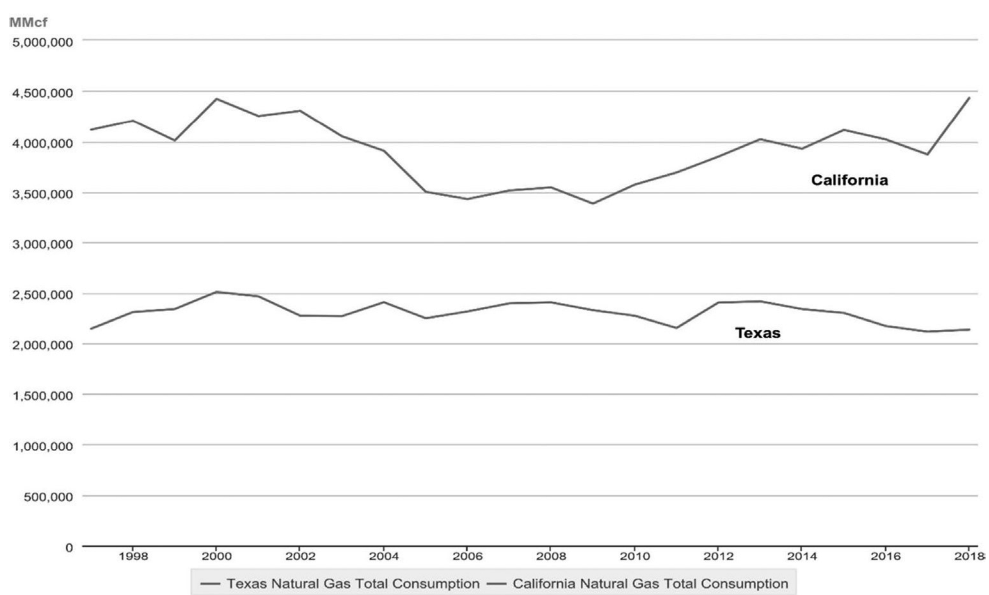
ROLE OF EXISTING H_2 PIPELINES

The alternative to blending H_2 in the existing natural gas grid is to rely on the existing H_2 pipeline network. This network was designed specifically for H_2 and its characteristics. The challenge of this approach is the limited size of H_2 pipelines and their ability to reach new customers.

There are close to 5,000 km (3,107 miles) of hydrogen pipelines around the world today, compared with approximately 3 million km (1.9 million miles) of natural gas transmission pipelines. These existing hydrogen pipelines are operated by industrial hydrogen producers and are mainly used to deliver hydrogen to chemical and refinery facilities. The United States has the largest H_2 pipeline network, which is over 1,500 miles long (**Figure 5**).

Most of the H_2 pipeline networks are located in coastal areas close to refineries and petrochemical plants they serve. The US Gulf Coast has the largest number of refineries (47) split between Texas (30)

Figure 4. Natural Gas Consumption in California and Texas



  / DOI 10.1002/gas

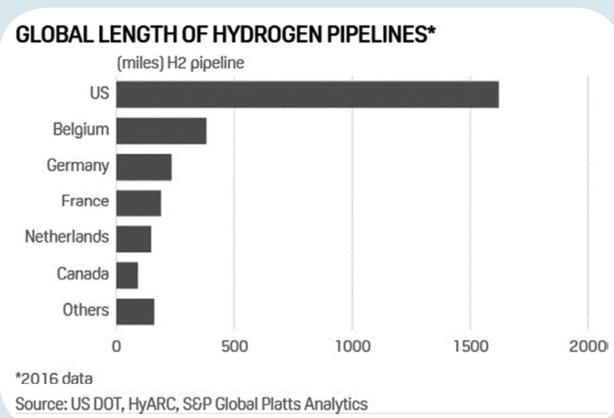
Table 4. CO_2 Emissions Reductions Achieved by Blending Hydrogen in California's Natural Gas Grid

% Blend of H2	5%	10%	20%	30%	50%	70%
Natural Gas in MMcf	221,628	443,255	886,510	1,329,766	2,216,276	3,102,786
Reduction in $CO_{2\,e}$ Emissions in Mt	12,160,285	24,320,515	48,641,031	72,961,601	121,602,632	170,243,662
% $CO_{2\,e}$ Reduction From 2017 Total California Emissions of 424.1 Million Mt	3%	6%	11%	17%	29%	40%

and Louisiana (17). California has 15 operating refineries. This author believes it might be prudent to examine the potential of expanding the existing H_2 pipeline network. For example, California's light-duty H_2 filling stations for FCEVs are being built in urban areas close to the coast. If green H_2 production facilities come online as expected, the existing network of H_2 pipelines and their expertise in transporting the fuel may benefit the program. Regardless, it might be beneficial for the CEC and CARB to discuss their supply needs with existing H_2 suppliers and pipelines.

Texas and Louisiana might also present opportunities to serve new H_2 customers and expand production to serve new customers such as FCEVs and heavy trucks. As stated earlier, the region has the most extensive H_2 pipeline system and knowledge about transporting the fuel, which could be invaluable to companies in Texas and Louisiana that wish to capitalize on the growing interest in H_2.

Figure 5. Length of Existing Global Hydrogen Pipeline Systems



THE DISCONNECT BETWEEN H_2 POLICY AND GREEN H_2 PRODUCTION SHORTAGES

Most current H_2 policies under development rely on green H_2 to decarbonize the natural gas and transportation system using FCEVs. However, the success of these policies depends on significantly increasing green H_2 production. As this author pointed out in Part 1, green H_2 is in short supply; therefore, the risk of H_2 policies failure is high. Any government body should be taking this into account before initiating such a plan of action. Indeed, this author believes that even the current or proposed efforts to investigate H_2 blending in the gas grid may be premature if green H_2 supplies are a limiting factor. The alternative would be to flow blue H_2 in gas grids and to supply H_2 fueling stations until such time that green H_2 production increases or to aggressively fund and incentivize green H_2 production through government incentives.

The CARB recognized a green H_2 production gap and the demand from its growing H_2 fuel stations in its 2017 and 2018 annual program reports.[16] In fact, a hydrogen supply disruption at one, caused by downtime at one facility in California between June 1 and October 4, 2019, decreased the amount of hydrogen available to FCEV drivers.[17] Air Liquide, Air Products,

[16] The California Air Resources Board's *Annual Evaluation of Fuel Cell Electric Vehicle Deployment and Hydrogen Fuel Station Network Development* in 2017 and 2018 at https://ww2.arb.ca.gov/resources/documents/annual-hydrogen-evaluation.

[17] California Energy Commission, California Air Resources Board. (2019, December). *Joint agency staff report on Assembly Bill 8: 2019 annual assessment of time and cost needed to attain 100 hydrogen refueling stations in California.* CEC-600-2019-039. Retrieved from https://ww2.energy.ca.gov/2019publications/CEC-600-2019-039/CEC-600-2019-039.pdf.

 DOI 10.1002/gas /

Praxair, Iwatani Corporation of America, and ITM Power have announced plans to deploy electrolyzers to produce renewable hydrogen for the California hydrogen refueling stations.

Data collected by the Pacific Northwest National Laboratory indicate that the hydrogen production capacity in California is generated for use in petroleum refining processes, either on-site or through a captured portion of the merchant hydrogen market.[18] Captive, on-purpose production at refineries and merchant gaseous hydrogen ultimately used in oil refining represent 4,700 Mt/day of daily production in California. These amounts dwarf the 26 Mt/day of liquid and 29 Mt/day of gaseous merchant H_2 sold for purposes other than oil refining.

Fortunately, California's H_2 policies are both pragmatic and grounded in reality. The amount of renewable or green H_2 dispensed in California's network of hydrogen refueling stations is almost 36 percent renewable. This level is stipulated in many CEC hydrogen solicitations and grant agreements per the intent of Senate Bill 1505. Therefore, the California network of hydrogen refueling stations meets and exceeds the required 33 percent renewable hydrogen standard for dispensed hydrogen by the California legislature.

The fulfillment of the state's renewable hydrogen requirement can be either in the form of Renewable Energy Certificates (RECs) or from the dispensing of renewable hydrogen produced directly from renewable sources. With limited sources and infrastructure available to secure hydrogen fuel from direct renewable sources, however, most of the fulfillment in California comes from the procurement of RECs.[19]

By all accounts, CARB's fuel cell station program is successful. CARB recommended that the CEC take steps to award funds to increase green H_2 production. On June 13, 2018, the CEC approved an award for a 100 percent renewable production facility under GFO 17-602. The facility will add 2 tons/day production capacity to a 3 ton/day facility already under development. The full project is expected to be developed in three phases.

This author believes that H_2 policies under development in other states and countries should be based on the current realities of H_2 production in their regions. Policy developers would be wise to follow California's model of setting goals for a percentage of hydrogen to be renewable. Demand rather than insisting on 100 percent green H_2. Policymakers should take note that the growth in BEVs has been successful, because there were no restrictions placed on BEVs to use only 100 percent renewable energy, nor have governments required that lithium-ion battery makers manufacture batteries and initially charge them only using renewable energy. Had they done so, the growth of BEVs might have been much lower.

CONCLUSION

H_2 blending in natural gas transmission and distribution lines could reduce CO_2 e emissions between 29 percent and 40 percent in California if implemented. However, gas utilities in general will require additional R&D on live natural gas systems to address pipeline integrity and safety as well as how blended H_2 will affect the performance of end-users. Gas utilities in California are interested in defining interconnection and injections tariffs with the California PUC but are hesitant to proceed absent real-time studies or regulatory approval.

Europe appears to be moving forward with H_2, as countries such as Germany, the United Kingdom, and France are pushing ahead with H_2 blending and an increased number of green H_2 projects. However, these countries are focusing more on green H_2 as a blending fuel than blue H_2. If the risks to natural gas pipelines from H_2 blending are not acceptable or the number of green H_2 projects do not materialize as planned, then countries and regulators may ultimately have no alternative than to rely on blue H_2 and/or expand the existing H_2 pipeline network.

Finally, countries and individual states should be cognizant that green H_2 is limited and sufficient supplies to blend in gas grids and for use by FCEV fueling stations in the early years of implementing such programs might not be possible. California's H_2 policy should be used as a model.

[18] US Department of Energy, Hydrogen Analysis Resource Center at http://hydrogen.pnl.gov/hydrogen-data/hydrogen-production and https://h2tools.org/hyarc/data

[19] Ibid., 2019.