Pathways and Challenges to Adoption of Decarbonized Hydrogen in Industrial Processes

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ABSTRACT

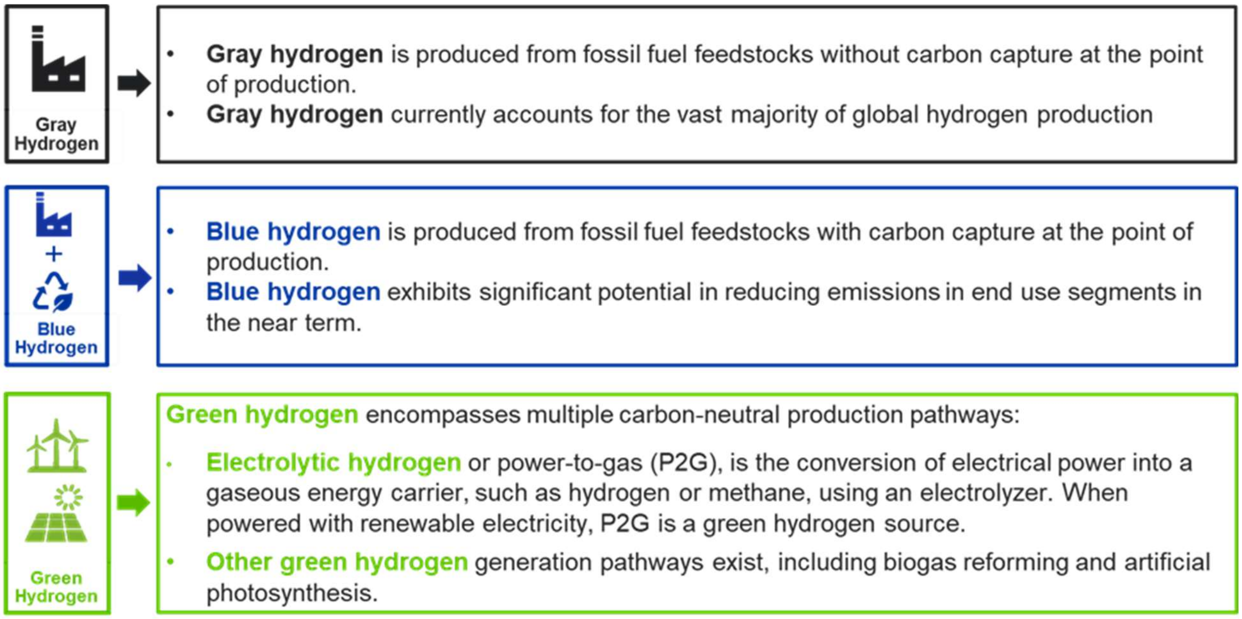
Decarbonized hydrogen has high potential as a low-carbon fuel for industrial processes and other difficult-to-electrify end uses. Hydrogen production, transport, and storage all present challenges, but as interrelated parts of the value chain, their solutions cannot be considered in isolation. We provide a comprehensive overview of the value chain for the application of hydrogen in industrial applications and describe the “virtuous cycle” of reliable demand, production, and transport necessary for widespread industrial use of decarbonized hydrogen.

Hydrogen production through green electrolysis or carbon capture currently adds a large cost premium relative to conventional methods. Because electricity cost dominates the price of electrolytic hydrogen, using renewable power that may otherwise be curtailed is one potential solution. Carbon capture, while currently more economical than green hydrogen production, faces economic and technical challenges. Furthermore, hydrogen’s low volumetric density presents major challenges for onsite fuel storage, making pipeline transportation critical. This favors geographically concentrated usage in industrial clusters. We also discuss the tradeoffs of blended fuel vs. pure hydrogen and natural gas pipeline repurposing vs. construction of new, dedicated pipelines. European gas transmission system operators favor transitioning to dedicated hydrogen pipelines primarily by converting existing gas infrastructure to accept hydrogen.

The Case for Low Carbon Hydrogen for Industry

On April 22, 2022 President Biden announced a 50% decarbonization goal by 2030 relative to 2005 levels (White House Briefing Room 2021). There has been strong support from industry (We Mean Business Coalition and Ceres 2021). Hydrogen has unique characteristics that position it well for addressing hard-to-decarbonize applications, including high-temperature combustion, cement production, and long-duration storage for backup electric power. There are also opportunities for pollution reduction beyond carbon dioxide (CO_2), including for example reductions in toxic metals, carcinogenic hydrocarbons, and particulates from cement production.

The three main source types ("colors") of hydrogen – gray, blue, and green – are defined in Figure 1. Hydrogen already serves an important role in industrial applications and can support decarbonization when green or blue hydrogen substitute for existing natural gas production in both incumbent hydrogen applications and new combustion applications.



- **Gray hydrogen** is produced from fossil fuel feedstocks without carbon capture at the point of production.
- **Gray hydrogen** currently accounts for the vast majority of global hydrogen production

- **Blue hydrogen** is produced from fossil fuel feedstocks with carbon capture at the point of production.
- **Blue hydrogen** exhibits significant potential in reducing emissions in end use segments in the near term.

Green hydrogen encompasses multiple carbon-neutral production pathways:

- **Electrolytic hydrogen** or power-to-gas (P2G), is the conversion of electrical power into a gaseous energy carrier, such as hydrogen or methane, using an electrolyzer. When powered with renewable electricity, P2G is a green hydrogen source.
- **Other green hydrogen** generation pathways exist, including biogas reforming and artificial photosynthesis.

Figure 1. Definitions of the three main source types (colors) of hydrogen. *Source:* Guidehouse

To enable and accelerate a transition to low-carbon hydrogen (blue or green), a virtuous cycle of **Demand, Production, and Transport** is needed (see Figure 2 below).

- **Demand** is generated through a combination of policy drivers and market forces pulling together to encourage adoption of decarbonized hydrogen. It will be critical for policymakers to shape long-term goals and set out appropriate incentives (direct and/or indirect) that industry and investors can count on over the long run.
- **Hydrogen production** technology advancements, in the form of more efficient and lower-cost means of generating low-carbon hydrogen, will also be critical to ensuring the economic feasibility of hydrogen. This can take the form of either carbon capture adaptations to existing gray hydrogen production facilities or electrolytic hydrogen produced using renewable energy,

- **Transport** of hydrogen, to supply industrial facilities, requires significant planning because of hydrogen's low volumetric energy density and extremely low boiling point. To minimize transport costs – or even in the short run to ensure adequate supply – onsite production may also be a solution, where there is sufficient space available for generation and storage infrastructure.

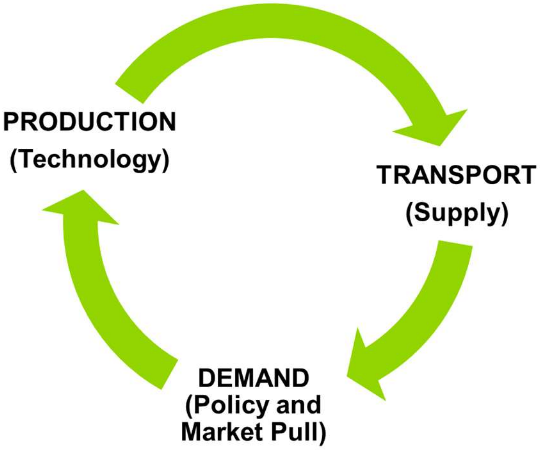


Figure 2. Virtuous circle for decarbonized hydrogen adoption. *Source:* Guidehouse

Figure 3 provides an overview of the hydrogen value chain in industrial applications, from feedstock through industrial end-use. Carbon capture, utilization, and storage (CCUS) processes for hydrogen production adds significant cost relative to gray hydrogen. However, deploying CCUS would extend the life of legacy hydrogen production assets that currently produce gray hydrogen through reforming processes (primarily of natural gas). CCUS can also further decarbonize hydrogen from bioenergy feedstocks, such as renewable natural gas and wood waste among other options.

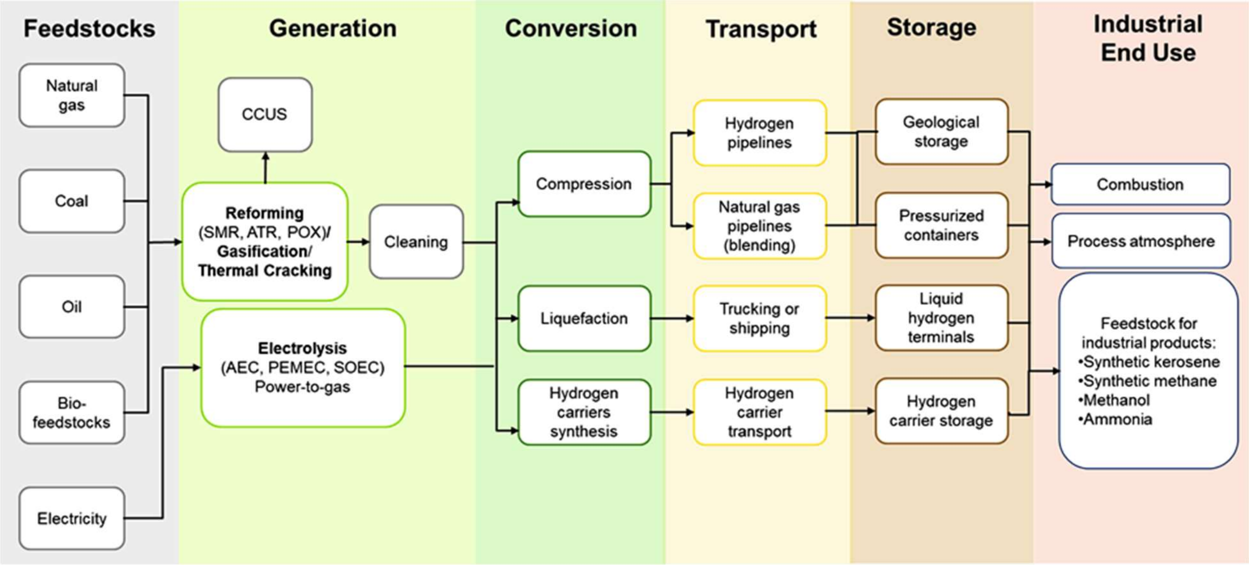


Figure 3. Overview of the hydrogen value chain in industrial applications. *Source:* Guidehouse

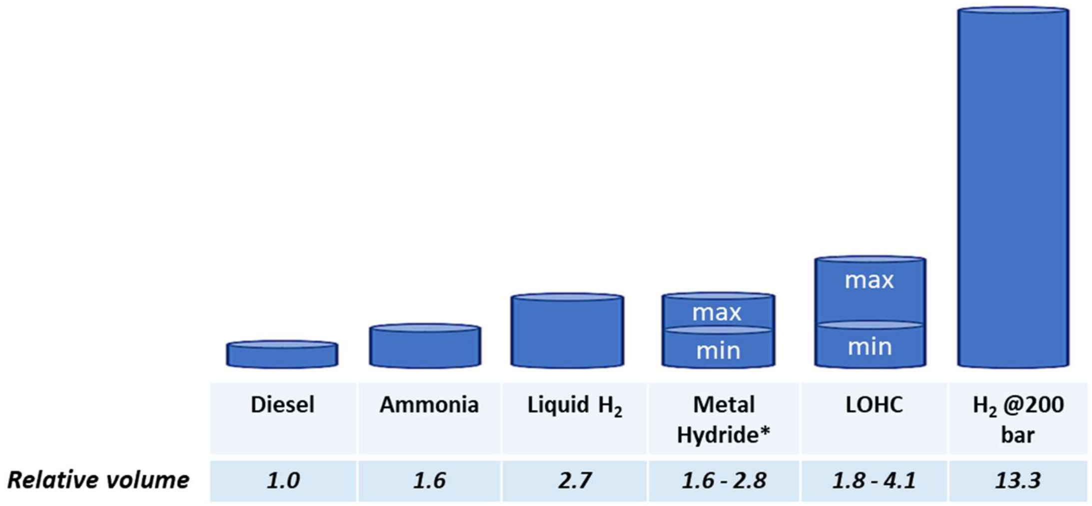
Hydrogen produced through reformers typically goes through a cleaning process to increase purity; on the other hand, electrolysis technologies such as alkaline (AEC), proton-exchange membrane (PEMEC), and solid oxide electrolyzer cells (SOEC) produce high purity hydrogen without further gas cleaning after the electrolyzer. AEC is currently the dominant electrolyzer technology, because of its cost efficiencies and technology maturity.

After production, the hydrogen needs to be converted into easy-to-transport forms, then transported to the site of end use via a variety of available and emerging methods, and finally stored. Storage can be done either strategically or onsite as a buffer prior to use. Existing hydrogen uses include, among others, as a process atmosphere (e.g., in glassmaking, metals, and electronic component fabrication) and as a feedstock (e.g., in refining and production of ammonia, methanol, and other chemicals). Emerging applications include the displacement of natural gas for industrial combustion applications. Industries such as steel, glass, and cement are investigating this type of application for hydrogen.

The Challenges of Transport and Storage

Gaseous hydrogen has very low energy density by volume, so onsite compressed hydrogen storage would require a much larger footprint than diesel fuel, the best comparison for backup power. Alternatives to storing hydrogen in gaseous form include managing it as a liquid at cryogenic temperatures or fixing it in hydrogen-rich chemicals such as ammonia or liquid organic hydrogen carriers (LOHCs). Storage in metal hydrides is also quite space efficient.

Figure 4 shows the relative volume required to store an equivalent amount of energy between diesel fuel and various forms of hydrogen or hydrogen-rich materials storage.



	Diesel	Ammonia	Liquid H_2	Metal Hydride*	LOHC	H_2 @200 bar
Relative volume	*1.0*	*1.6*	*2.7*	*1.6 - 2.8*	*1.8 - 4.1*	*13.3*

* Theoretical maximum volume for metal hydride

Figure 4. Equivalent energy content of various energy storage options. *Source:* Guidehouse

Applying an “Anchor Customers” model with industrial clusters of concentrated demand will reduce risk and improve the economics of the hydrogen gas supply that needs to be built out. Concentrating the industrial users of hydrogen in close geographical proximity to each other facilitates decision making for gas suppliers through simpler logistics and greater certainty of demand which improve economics by increasing the scale and reducing risk. This also better ensures adequacy of supply until such time as centralized generation of hydrogen with delivery via extensive pipeline systems exists. In some parts of the country, this will represent a shift in the considerations used for locating of new industrial facilities. Guidehouse is aware of at least one U.S. industrial cluster project that is taking issues related to decarbonization into account for siting. Table 1 below provides an overview of nine electrolytic hydrogen projects. These projects are examples of local and onsite electrolytic hydrogen production that are partly or completely designed for industrial applications.

Table 1: Examples of industrial electrolytic hydrogen projects

Project	Location	Year Operational	Electricity	Facility Type	Capacity
e-gas (Audi)	Werlte, Germany	2014	Wind energy	Synthetic methane via green H_2 and CO_2	2.7 tonnes of synthetic CH_4 per day (avg)
H2FUTURE	Linz, Austria	2019	Renewable electricity	Steel production	2.6 tonnes H_2 per day
HyBalance	Hobro, Denmark	2020	Wind energy	Multiple users (grid, industry, transport)	0.5 tonnes H_2 per day
Refhyne Shell Refinery	Cologne, Germany	2021	General supply	Refinery	3.5 tonnes H_2 per day
Iberdrola	Puertollano, Spain	2021 (expected)	Solar PV	Ammonia production	2 tonnes H_2 per day
Port of Rotterdam (BP refinery)	Rotterdam, Netherlands	2022 (expected)	Renewable electricity	Refinery	120 tonnes H_2 per day
CF Industries Green Ammonia	Louisiana, USA	2023 (expected)	Renewable electricity	Ammonia production	6.5 tonnes H_2 per day
Westküste 100 Heide Refinery	Schleswig-Holstein, Germany	2025 (expected)	Offshore wind energy	Refinery	168 tonnes H_2 per day
NEOM	Neom, Saudi Arabia	2025 (expected)	Solar and wind energy	Ammonia production and transport	650 tonnes H_2 per day

In Europe, major gas transmission system operators (TSOs) have proposed a hydrogen roadmap that foresees nearly 70% of the natural gas infrastructure being repurposed for hydrogen transport (Guidehouse 2021), as shown in Figure 5. The focus is on converting existing natural gas (NG) pipelines, using reduced NG usage and alternative delivery routes available in the mesh delivery network to make the transition. The cost of retrofit is between 10-25% of the cost of new hydrogen pipelines, not considering compression costs nor any hydrogen separation at the delivery side when gases are blended.

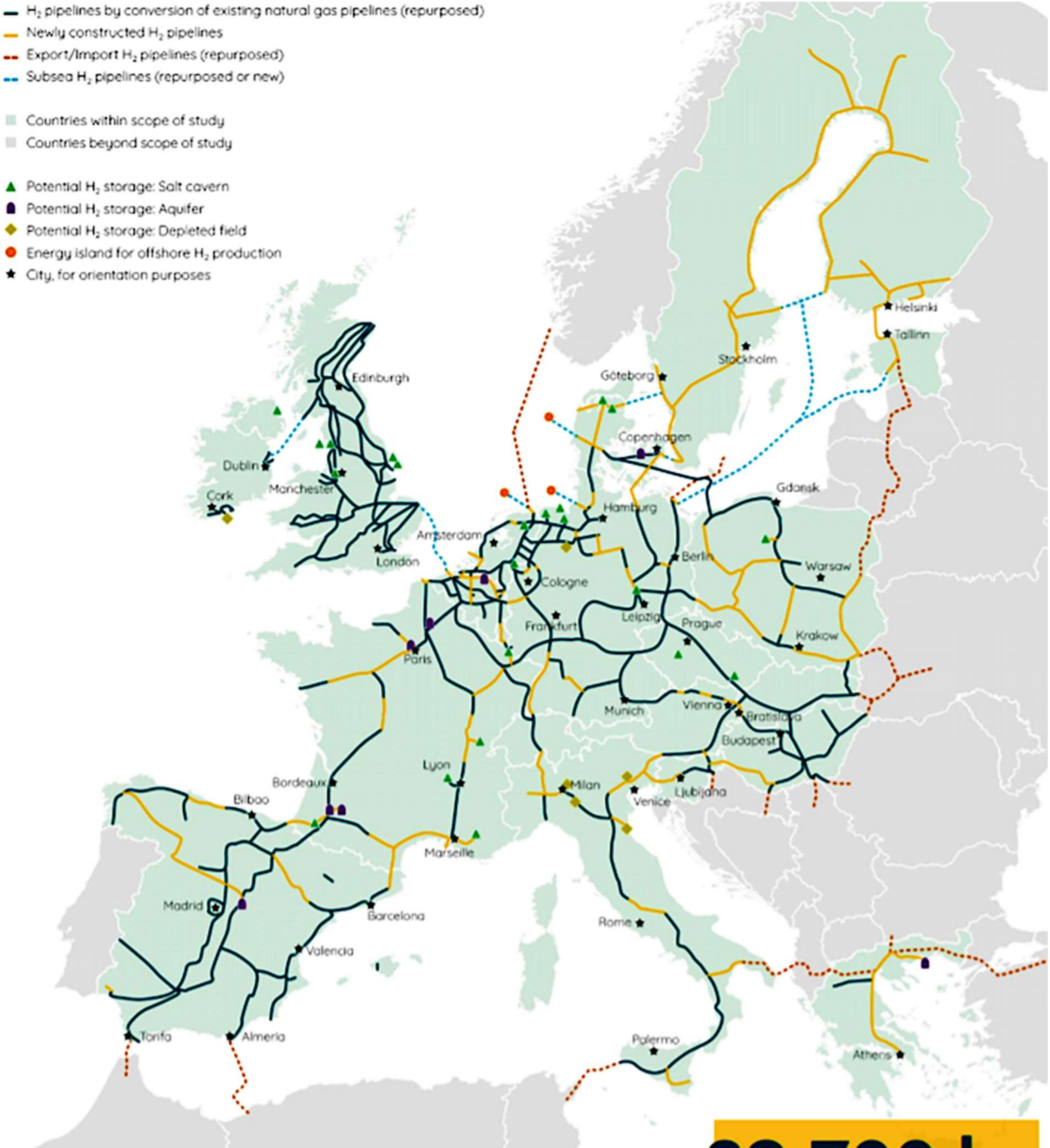


Figure 5. Proposed European hydrogen backbone structure. *Source:* (Guidehouse 2021)

It should be noted that blending hydrogen with natural gas is looking increasingly unattractive to EU actors, given the complications it would create for existing equipment that is sized, designed, and calibrated for natural gas, as well as the related safety systems. Pricing blended gas based on volume may be problematic, as the energy content of the delivered gas can be inconsistent as the concentration of hydrogen in the gas will likely vary.

These insights, and other lessons from Europe, will provide crucial background for the U.S. with respect to any potential build-out of dedicated hydrogen pipeline infrastructure beyond that which currently exists. To the extent it is possible, achieving decarbonization by leveraging existing assets and sources of demand would facilitate the upgrade process.

The Challenge of CCUS and Promise of Renewables-powered Electrolysis

Carbon Capture Utilization and Storage (CCUS) is generally viewed as the most effective near-term solution to providing decarbonized hydrogen into the marketplace. If offtake parties that can use the captured CO_2 exist, CCUS' price premium to gray hydrogen can be minimized. However, when CO_2 must be stored long-term or sequestered the costs can increase dramatically, and geological suitability must be considered for carbon storage and sequestration activities.

The U.S. Department of Energy (DOE) has funded the National Renewable Energy Lab (NREL) and Strategic Analysis to conduct an Analysis of Advanced H_2 Production & Delivery Pathways (Strategic Analysis 2020). Insight from this analysis is that adopting newer, more innovative – but also more expensive – technologies for electrolysis is viable if electricity costs can be reduced and equipment utilization stays high (97% in the DOE H2A model). Storage and movement of hydrogen are separate considerations not included in the study. See Figure 6.

The importance of electricity input costs to the economics of electrolytic hydrogen makes Solid Oxide Electrolysis (SOE, which is still emerging relative to Alkaline and PEM electrolysis) potentially attractive. SOE can utilize waste heat or steam to significantly reduce the amount of electricity required, while also increasing overall efficiency.

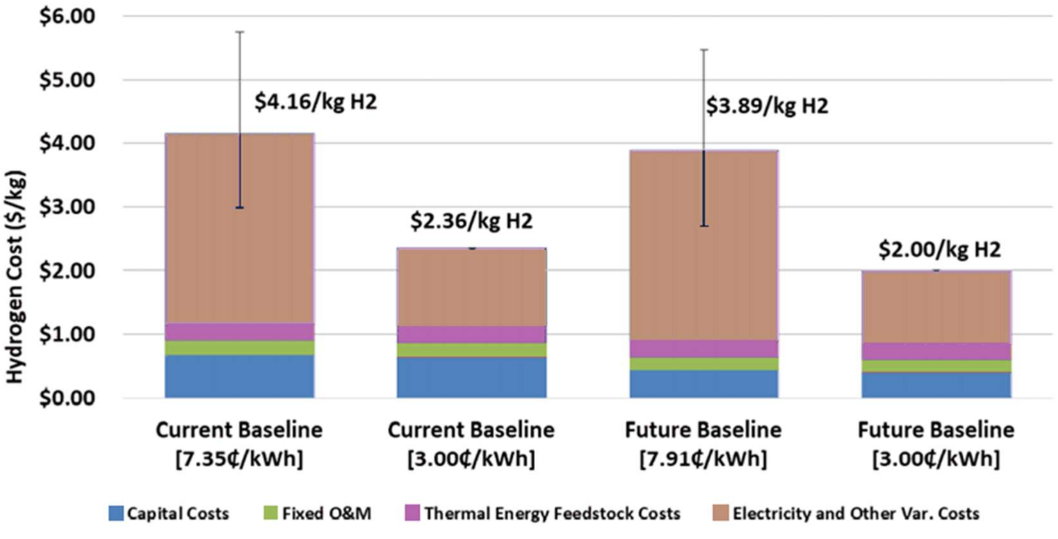


Figure 6. Solid Oxide Electrolyzer (SOE) hydrogen cost analysis (H2A) results, central cases.
Source: (James et al. 2020)

Low-cost renewable power is essential to the economic viability of green hydrogen production, and it may be provided by photovoltaic solar, concentrating solar, onshore wind, or offshore wind assets. In addition to production of hydrogen for use by industry, electrolyzer utilization may be further boosted if the equipment is used to help in reducing curtailment of intermittent renewable resources during low and shoulder periods of demand. The hydrogen thus produced could be stored and used later with a fuel cell or hydrogen-capable generator to help firm up power grid capacity during times of high demand.

Non-Combustion and Combustion Applications for Hydrogen

Non-combustion applications of hydrogen include its use as a chemical and fuel feedstock, a process atmosphere, and a heat transfer enhancement substance. Hydrogen is commonly used in petroleum refining, glassmaking, metal heat treatment, chemical and materials manufacturing, electronics manufacturing, and the production of fertilizer and fuel products like ammonia and methanol. These are currently the dominant applications of hydrogen, and an opportunity exists to apply emerging supplies of blue and green hydrogen to displace the gray hydrogen used for these non-combustion applications.

While still relatively rare, applications for hydrogen can include its use as a fuel, in two major ways: (1) for multi-purpose combustion equipment such as boilers, air heaters, process heaters, and thermal and catalytic oxidation, and (2) industry-specific combustion equipment such kilns, furnaces, ovens, and other combustors for production of products such as cement, glass, and metals. The metrics needed to characterize combustion systems also fall into two categories, being: (1) the functional performance metrics for the equipment, such as process performance, emissions, energy efficiency, and cost, and (2) combustion metrics such as flashback potential, burner and flame stability and control, radiative heat transfer of the flame, combustion gas wetness, system materials compatibility, etc. See Table 2 below.

Table 2: Some of the barriers to H_2 adoption in industrial combustion equipment

Potential Barriers	Sensitive Sectors	Enablers
Heat transfer – convective vs. radiative	Glass, ceramics, and lime	Further experimental investigation on heat transfer balance in glass furnaces and kilns.
NOx emissions	All	Flue gas recirculation, steam addition and post-combustion treatment (SNCR & SCR) can be used. Further work on low NOx burners may also reduce emissions.
H_2 burner manufacturers	All except chemical and refinery examples	Further research and development by burner manufacturers. This requires a future commercial market.
H_2 burner materials	All	No new action – materials currently exist and have been used
Flue gas moisture content	Ceramics, food and drink, vehicles, lime	Specific product demonstration trials required within relevant sectors
Gas engine conversion	Sites with gas engines	Period of research and development, small/large scale trials. Potential appliance replacement.
Pipes and fittings	All	No new action – materials and standards currently exist.

Source: (Durusut and Moore 2019)

The level of H_2, blended with natural gas, that can be tolerated by different combustion systems will vary and should be carefully explored by industrial equipment manufacturers, process designers, safety engineers, regulators, and end-use customers.

Conclusions and Recommendations

Decarbonized hydrogen will become an increasingly common input in industrial processes over time, going beyond hydrogen's traditional role in petroleum refining and ammonia production. It is important that industrial energy consumers prepare for the future through forward-looking activities such as: (1) maintaining awareness of the state of hydrogen adoption, keeping an eye on the U.S., Europe and Japan and all industries with similar processes (e.g., the use of process heaters or high-temperature furnaces); (2) noting when legal and political drivers, such as GHG reduction targets and carbon incentives, are put in place; (3) strategic planning, using the prior two steps to guide development of likely scenarios for analysis; (4) process and operational studies to understand the costs, benefits, potential barriers, and possible solutions that might arise relative to adoption of green (or blue) hydrogen; and (5) development of a change management approach to minimize the overall cost of switching to green or blue hydrogen from grey hydrogen or natural gas.

If and when it looks likely that your industry will be shifting toward adoption of hydrogen, experience shows that it is critical to create partnerships with equipment manufacturers, gas providers (natural gas utilities and industrial gas suppliers), and others to ensure adequate supplies of decarbonized hydrogen at low cost. Be engaged in the discussions of the demand, production, and transport aspects of decarbonized hydrogen to ensure your enterprise is well served in the years to come.

Demand

Growing the demand for decarbonized products will require steady policy support, reinforced by market forces. To activate the demand portion of the adoption cycle, policymakers need to set goals, create incentives to decarbonize, and facilitate the introduction of carbon pricing.

Complementary strategic vision and leadership from industry (e.g., end-use industrial customers and gas utilities) is needed to align operations and investments with policymakers. Clustering industrial facilities that need hydrogen with local or onsite supply will support economics and make planning easier.

At the end-user level, it will be important to have a game plan ready for fuel flexibility or a direct transition to hydrogen.

Production

Onsite, local-centralized (industrial cluster), or distant-centralized production of hydrogen can have different operational and economic impacts on end-users and differing timelines for development. From a technology perspective, the cost of electrolysis equipment needs to be reduced further, especially for SOEs. Production efficiency needs to be increased through higher electrolyzer current densities, which results in more hydrogen being produced per ampere of current used. These factors are important for the long-term growth prospects of green electrolytic hydrogen. The cost of CCUS also needs to be reduced to support the gradual conversion of gray hydrogen to blue hydrogen, where green hydrogen is not yet feasible.

Most importantly, to ensure adequate clean hydrogen supply the production of electrolysis-based hydrogen will require large-scale access to low-cost electricity from renewable power sources such as solar and wind. Access to excess electricity generation during off-peak periods will support improved economics, but in addition a steady supply of low-cost, clean electricity is even more important for electrolyzer project feasibility. This will require sharing of planning and development costs across sectors including electricity, gas, and industrial end users.

Transport

Based on the European experience, the transportation of hydrogen should make maximum use of the existing gas transmission, distribution, and storage infrastructure. However, in practical terms "maximum use" may be less than desired or needed, limited at first perhaps to gas mesh networks where both hydrogen and natural gas can reach customers. In many areas of the U.S., it is difficult to obtain new rights-of-way for dedicated hydrogen pipelines (Parfomak 2021), so using existing pipeline infrastructure wherever possible will be the only practical pathway to transporting hydrogen using pipelines in the medium term. Onsite storage of significant amounts of hydrogen will be challenging, and if feasible requires balancing the volumetric energy density, equipment cost, and handling requirements at a given site.

Final Thoughts

In conclusion, the production of blue and green hydrogen and their application in industrial settings will be important components of the nation's efforts to achieve its climate goals in the coming years. Adoption of clean hydrogen for both existing and new applications presents significant challenges of production, transport, and storage, and without a market demand none of those challenges are likely to be surmounted. Once demand, production, and transport are all in place and balanced, sustainable growth in adoption is likely to ensue. The checks on hydrogen adoption growth will ultimately need to be competing decarbonization technologies and the achievement of complete decarbonization throughout the industrial sector, rather than a failure to have the proper hydrogen ecosystem factors in place.

Stakeholders across the value chain should examine their operations going forward and re-evaluate on a regular basis whether integrating decarbonized hydrogen into their operations is feasible, desirable, or necessary.

References

Durusut, E., and Moore, I. 2019. *Hy4Heat WP6 Understanding Industrial Appliances Workshop*. United Kingdom: Department for Business, Energy & Industrial Strategy. https://static1.squarespace.com/static/5b8eae345cfd799896a803f4/t/5caf309a652dea64b686e278/1554985118652/BEIS+Hy4Heat+WP6+-+industry+workshop+handout+F.pdf.

Guidehouse. 2021. *Extending the European Hydrogen Backbone*. Ultrecht, Netherlands: Gas for Climate. https://gasforclimate2050.eu/wp-content/uploads/2021/04/European-Hydrogen-Backbone-2021-Webinar-slidedeck.pdf.

James, B., DeSantis, D., Huya-Kouadio, J., Houchins, C., and Saur, G. 2020. *Analysis of Advanced Hydrogen Production and Delivery Pathways*. Arlington, VA: Strategic Analysis, Inc. https://www.hydrogen.energy.gov/pdfs/review20/p102_james_2020_o.pdf.

Parfomak, P. 2021. *Pipeline Transportation of Hydrogen: Regulation, Research, and Policy*. Washington, DE: Congressional Research Service. https://crsreports.congress.gov/product/pdf/R/R46700.

We Mean Business Coalition and Ceres. 2021. "408 Businesses and Investors Support U.S. Federal Climate Target in Open Letter to President Biden." New York: We Mean Business Coalition. April 13. https://www.wemeanbusinesscoalition.org/press-release/businesses-investors-support-u-s-federal-climate-target-open-letter-president-biden/.

White House Briefing Room. 2021. "FACT SHEET: President Biden Sets 2030 Greenhouse Gas Pollution Reduction Target Aimed at Creating Good-Paying Union Jobs and Securing U.S. Leadership on Clean Energy Technologies." Washington, DC: The White House. April 22. https://www.whitehouse.gov/briefing-room/statements-releases/2021/04/22/fact-sheet-president-biden-sets-2030-greenhouse-gas-pollution-reduction-target-aimed-at-creating-good-paying-union-jobs-and-securing-u-s-leadership-on-clean-energy-technologies/.