ENERGY SYMPOSIUM SERIES

The Gulf Coast Hydrogen Ecosystem: Opportunities and Solutions

Authored by Paul Doucette

UH Energy
UNIVERSITY OF HOUSTON

Energy Transition Institute
UH ENERGY

TIEEP
TEXAS INDUSTRIAL ENERGY EFFICIENCY PROGRAM

Table of Contents

About the Author

Paul Doucette is the Hydrogen Program Officer in the Division of Energy and Innovation at the University of Houston. Prior to joining the University, he spent over 50 years in the oil and gas industry, working in petroleum, the energy transition, policy, and government affairs management. In his previous role at Baker Hughes, he held an executive leadership position involving energy transition.

Contributors

The following individuals were members of the planning team for the hydrogen symposium and assisted by extending invitations to speakers and participants, acted as presenters, moderators, and/or session chairs, and contributed important content to this report.

- **Mr. Greg Bean,** director, Gutierrez Energy Management Institute, C.T. Bauer College of Business, UH
- **Dr. Gail Buttorff,** associate director, Center for Public Policy, Hobby School of Public Affairs, UH
- **Dr. Joe Powell,** founding executive director, Energy Transition Institute, UH
- **Dr. Ram Seetharam,** executive director, ROICE Program, UH Energy
- **Dr. Alan Rossiter,** executive director, external relations, and educational program development, UH Energy
- **Mr. Melvin White,** president, MRSW Management

Acknowledgements

The author and members of the planning team would like to thank and acknowledge Dr. Deidra Perry and her team, particularly Riane Harris and Ed Bailey IV, for their assistance with the planning, organization, and execution of the symposium. Finally, we acknowledge the support of the following students for their service in taking notes, which served as the basis for this report.

- **Mustafa Khan** - Mechanical Engineering
- **Prince Aleta** - Environmental Engineering
- **Shamin Sadat Hosseini** - Chemical Engineering
- **Aanchal Jaggi** - Bauer MBA, Concentration in Business Analytics
- **Seyedborhan Mousavi** - Chemical Engineering
- **Vinay Nagulavancha** - Bauer in Finance
- **Shreedevi Nandam** - Bauer MS in Business Analytics
- **Emo Obadiah** - Chemical Engineering
- **Ricardo Plata** - Bauer BBA in Supply Chain
- **Jehoiarib Umoren** - Bauer MS Supply Chain
- **Mohan Ranganadh Vedala** - Bauer MS in Business Analytics
- **Ana Vielma Amarista** - NSM PhD in Geology

Executive Summary

In 2023, the U.S. federal government announced a $7 billion investment in seven Regional Clean Hydrogen Hubs (H2 Hubs) to accelerate the commercial-scale deployment of low-cost hydrogen as part of the Investing in America agenda. This includes funding and program support from the American Rescue Plan, Bipartisan Infrastructure Law, CHIPS and Science Act, and Inflation Reduction Act. The HyVelocity Hub in Houston was selected as one of the hubs and could receive up to $1.2 billion in federal funding.

Houston and the Texas Gulf Coast have the opportunity to continue to lead the global hydrogen economy. The knowledge and experience of being the leading hydrogen producer in the world with more than 1000 miles of dedicated hydrogen pipeline connecting to 48 hydrogen production facilities and three significant salt cavern storage, Houston and Texas, which are fast becoming the nation's leading hub for renewable electricity generation, are well-positioned to continue its global hydrogen dominance. The HyVelocity Hub aims to move the federal initiative to rapidly scale a clean hydrogen value chain with a clear objective to reduce carbon emissions to less than 2 kilograms per kilogram of hydrogen within a decade and fulfill the promise of the Justice40 initiative and prioritize community engagement. The HyVelocity Hub is also expected to create approximately 45,000 direct jobs. Of these, 35,000 are in construction and 10,000 are permanent jobs. Building on this baseline, advocates have set key goals to guide the development of Texas as a global hydrogen hub by 2050. These include:[i]

- Reaching 21 million tons per year (Mtpa) of clean hydrogen production, with 12 Mtpa meeting local demand and 9 Mtpa for exports;
- Creating 180,000 direct, indirect, and induced jobs;
- Abating 220 Mtpa of carbon dioxide globally, which is four times the state's current carbon emissions;
- Creating $100 billion in additional economic value, which is 5% of the state's GDP in 2023.

Meeting these goals will require large, complex capital projects and unprecedented levels of planning, collaboration, and adoption among many players.

Among the key considerations:

- At least some of the announced clean hydrogen projects are likely to be delayed. In the U.S., uncertainty about tax credits, lengthy lead times for permitting, equipment delivery, and other logistical issues, may push the operational date to 2032 or beyond.
- Current technology can produce enough hydrogen to meet near-term goals, but costs must be reduced for large-scale competitiveness. Achieving this will require new technologies and updated regulatory, permitting, and policy frameworks.
- Significant opportunities lie in reducing emissions in heavy industry, energy storage, power production, heavy vehicle transportation, export markets, marine applications, and low-carbon ammonia.
- Community engagement is critical with a federal initiative requiring 40% of the benefits of clean energy projects, including those involving hydrogen, to be targeted to disadvantaged communities. With this and the federal government's Justice40 goals, companies must prepare for extensive outreach and collaboration.
- Workforce development will be part of that outreach as the industry builds a skilled hydrogen workforce. The required training for this workforce can be delivered through a variety of mechanisms, from apprenticeships to job training programs, community programs, colleges and universities, and in-house.
- Hydrogen and other low-carbon energy industries have the potential to attract incoming and future workforce interested in impact decarbonization and climate mitigation solutions.

Symposium Focus

The Division of Energy and Innovation at the University of Houston organized a symposium exploring the hydrogen ecosystem along the Gulf Coast on April 17, 2024, as part of the Critical Issues in Energy 2023-2024 Symposium Series. The purpose was to better understand challenges and opportunities emerging in the field, focused on technology, business, policy, safety, and regulatory issues, community engagement, and workforce development.

Participants included representatives of national laboratories, academia, think tanks, and hydrogen thought leaders from the United States and Europe, with additional representation from government agencies and local communities. Sessions were conducted under the Chatham House Rules.

This report is based on information from the symposium. Slides used during the presentations are available at https://www.uh.edu/uh-energy-innovation/uh-energy/energy-symposium-series/2023-2024/hydrogen-ecosystem/

Background

Hydrogen is used for a wide range of applications, including oil refining, ammonia production, methanol production, and steel production. The use of hydrogen in transportation, through fuel cells and as rocket fuel, as well as in utilities for electricity generation, and as a fuel for industrial and residential heat are currently niche markets. Already global production capacity for clean hydrogen has increased 17% since mid-2023. More than 1,400 projects have been announced, mostly in Europe and North America, with a projected production of 45 million tons per year of clean hydrogen by 2030.

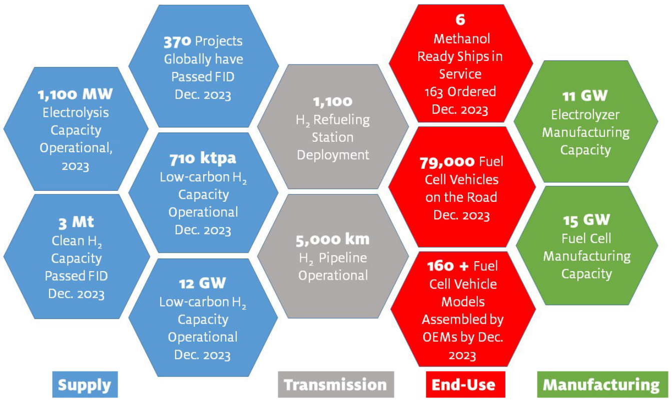

Figure 1. Growth of the global hydrogen ecosystem
Source: McKinsey and Company and Hydrogen Council

Continued growth will not be cheap – globally, more than $570 billion in investments will be needed just to develop the announced projects by 2030. And even that will not be enough to reach Net Zero by 2050. The Hydrogen Council, a group of 140 companies representing the full hydrogen value chain, estimates reaching Net Zero will require 225 gigawatts of hydrogen electrolysis capacity. Current capacity is expected to reach slightly more than half that, 120 gigawatts, by 2030. Completing announced projects will depend on the availability of additional financing, infrastructure debottlenecking, and additional policymaking and clarification.

In the U.S., most commercial hydrogen ("gray" hydrogen) produced is from natural gas through steam methane reforming (SMR). When the carbon emissions produced by this process are captured and stored through CCS (Carbon Capture and Sequestration) instead of being emitted into the atmosphere, the result is "blue" hydrogen. Alternatively, autothermal reforming (ATR) is of growing interest and uses natural gas to produce "blue" hydrogen with low carbon intensity. "Green" hydrogen is produced using carbon-free electricity from renewable sources, such as wind or solar, to split water into two hydrogen atoms and one oxygen atom, a process known as water electrolysis.

Hydrogen produced by renewable energy and electrolysis requires significant energy input to split water molecules and is more energy-intensive than production from natural gas. The additional energy demand substantially increases the cost of clean hydrogen.

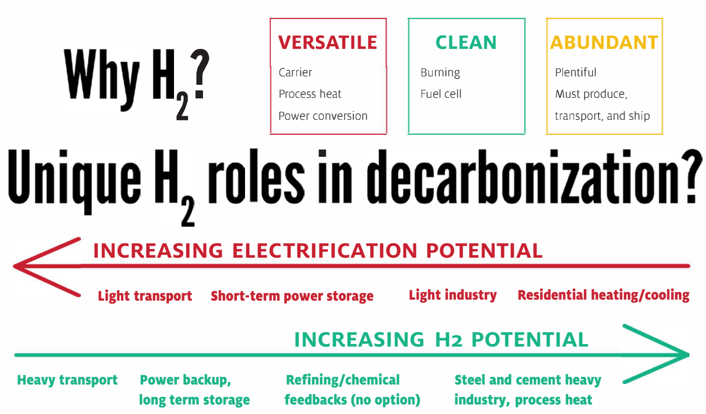

Figure 2. Properties of hydrogen and its unique role in decarbonization
Source: from UH-CHF Report with Andy Steinhubl.[ii]

A yet-to-be-exploited option is subsurface geologic hydrogen that can be found in collected pools or be induced via ingress of water to iron-rich source rock.

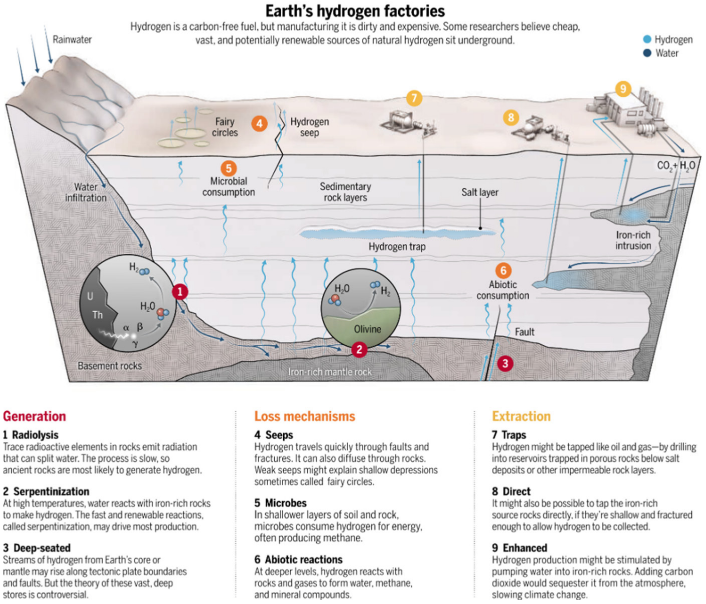

Figure 3. Geologic Hydrogen: schematic describing generation, loss, and extraction
Source: Hand, 2023.[iii]

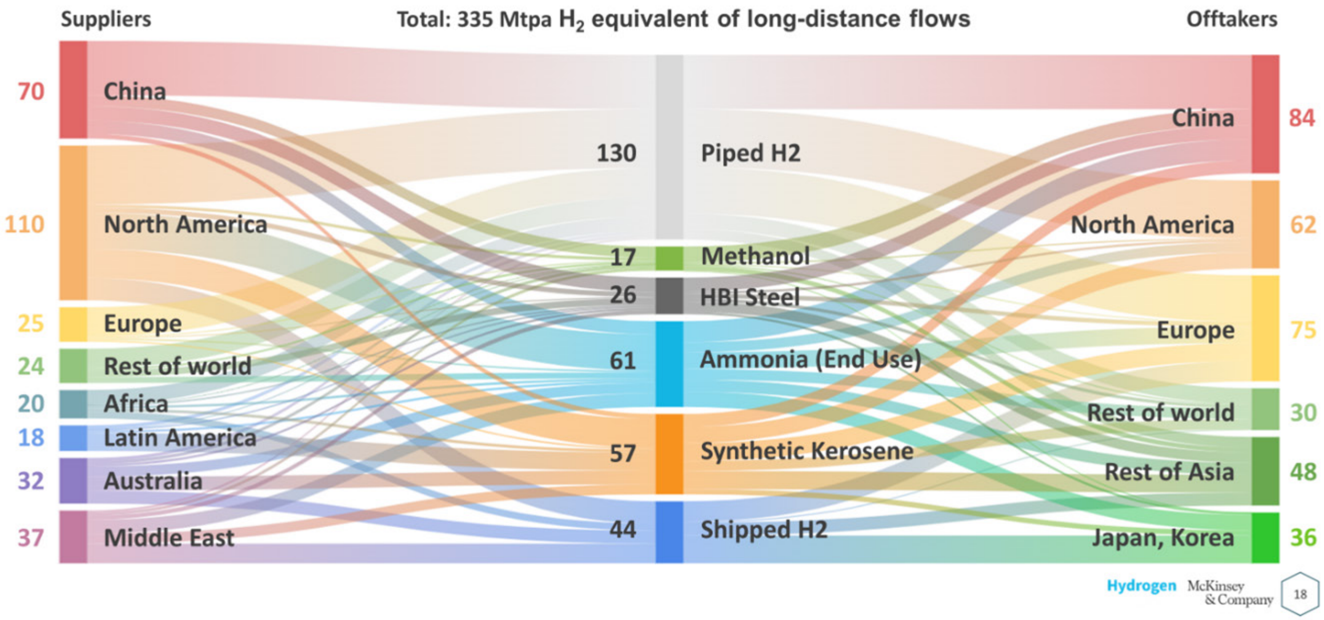

Figure 4. Global hydrogen and derivate long-distance trade flows, 2050 MTPA H_2 equivalent
Source: Hydrogen Council in collaboration with McKinsey & Company

The Business Case for Hydrogen

Houston and the Texas Gulf Coast represent about 30% of the national refining capacity. While the refining and petrochemical industries are the current dominant hydrogen users in the region, the key opportunities for the desired industrial decarbonization are in hard-to-abate sectors like steel production, and heavy-duty transportation, including trucking, aviation, and shipping. Three nascent markets in the region are also likely to grow significantly. These are:
a) hydrogen as a transportation fuel
b) hydrogen as a vector for long-duration energy storage, and
c) a global market for hydrogen through exports.

By 2050, an estimated 335 metric tons of clean hydrogen and its derivatives will be annually transported over long distances.[iv]

The opportunities for Houston and the broader Gulf Coast to become a global hub for producing and exporting hydrogen are enormous. The regional advantages range from abundant natural resources to existing infrastructure, which can give Houston a head start in developing a leadership position. Inexpensive and abundant natural gas is a critical feedstock for producing blue hydrogen via SMR with CCS.

The state is also a leader in wind and solar energy, which provide unmatched potential for low-cost renewable electricity to power water electrolysis. These existing assets, combined with the large petrochemicals and refining base spread across the Gulf Coast, can enable the efficient integration of the hydrogen supply chain with current operations. Using hydrogen at manufacturing plants in the region will also significantly lower emissions.

The Gulf Coast benefits from deep and broad industry expertise, from major oil and gas companies to industrial gas suppliers and equipment manufacturers. This industrial backbone, combined with the region's status as an energy innovation hub means that with adequate retraining, the hydrogen economy can be built upon existing workforce capabilities and leverage current energy industry knowledge. Similarly, the existing base of equipment manufacturers, engineering/design/construction firms, and operations and maintenance support service providers can be redirected to support the new low-carbon hydrogen supply build-out.

Houston's Hydrogen Advantage

Energy Assets	Production Capacity	Transportation, Storage, and Use
33% of U.S. H_2 Production Capacity (48 plants)	Largest Renewable Energy: 36 GW Wind & 15 GW Solar	1000+ miles H_2 Pipelines
11% of U.S. Energy Jobs	2.4 Billion tons of CO_2 Storage Capacity	3 H_2 Storage Caverns (50% of Global Sites)
7000+ Energy Manufacturing Cluster	11.2 Tcf Natural Gas Produced in 2022	29% of U.S. Refining Capacity in Texas Gulf Coast

Figure 5. Houston and the Gulf Coast are well-positioned to lead the Hydrogen Economy
Source: Adapted from the HyVelocity Hub and the Greater Houston Partnership.

Translating those assets to a hydrogen economy, however, will not be seamless. An estimated $570 billion in investments will be needed to develop the announced projects by 2030. While the need for massive investment in low-carbon hydrogen production facilities is one of the key considerations for this transition, it is far from the only one. Workforce development and training programs will be vital to ensure the region has the skilled labor needed to construct and operate hydrogen facilities. Successful community engagement, driving community acceptance and support, will be equally critical.

To drive investment and community acceptance, the current regulatory uncertainty facing the developing industry must be addressed. While the Section 45V tax credit for clean hydrogen is critical for drawing investment, it is not yet clear as to how it will be applied.[v]

Furthermore, requirements around renewable energy integration and stringent emissions thresholds could hinder early project development. A stable and predictable policy environment will provide the necessary confidence for investors and project developers to commit to hydrogen projects.

It is noteworthy that large projects typically require about ten years from conception to operation. Delays caused by uncertainty about the tax credits, and long lead times for permits, equipment delivery, and other logistical issues are likely to delay the projects to 2032 or beyond.

Nevertheless, the outlook for demand is strong. The Gulf Coast, with its extensive energy infrastructure and access to ports, is uniquely positioned to become a major hub for hydrogen production and export, particularly for hydrogen destined for Europe and Asia. A recent National Petroleum Council (NPC) study projected that U.S. hydrogen demand could increase seven-fold, to 75 million metric tons, by 2050 in a Net Zero emissions scenario, with 60% of demand coming from Texas and Louisiana. U.S. demand will be driven largely by hard-to-abate heavy industrial sectors, including refining, chemicals, cement, and steel.

Other key opportunities include:

- Energy storage and power production: Renewable energy from wind and solar sources is increasing on the ERCOT (Electric Reliability Council of Texas) grid, which serves most of Texas. These loads are highly variable, and dispatchable power production using stored hydrogen provides a mechanism for balancing the grid.

- Transportation, especially for heavy vehicles, export markets, and fueling port activities: The potential for hydrogen corridors, connecting ports and goods distribution centers, could facilitate the growth of hydrogen refueling infrastructure and accelerate the adoption of hydrogen-powered vehicles.

- Low-carbon ammonia or other hydrogen derivatives can meet the demand for low-carbon shipping fuel: The development of large-scale e-fuel facilities can help meet the demand for sustainable aviation fuels.

While continued technology development and economies of scale will reduce costs, challenges remain from a business standpoint. The NPC study noted that significant additional government policy support will be necessary to drive down the cost of clean hydrogen production.

High transportation costs may also limit demand growth in that sector. The development of hydrogen hubs, where production, storage, and end-use applications are co-located, could minimize transportation costs and risks. These hubs could serve as the foundation for regional hydrogen clusters, connected by dedicated hydrogen pipelines, and foster the growth of a hydrogen economy. Currently, the lack of existing contractual mechanisms for long-term offtake/purchase agreements has made financing for hydrogen projects difficult. Collaboration among asset owners, technology providers, engineering and construction firms, and financial institutions will be needed to de-risk projects and attract investment.

Beyond production, challenges related to distribution must also be addressed to ensure widespread demand for clean energy and the resulting investment opportunities. The Gulf Coast has the largest network of hydrogen pipelines and storage facilities in the nation, and leveraging this existing infrastructure provides unheralded opportunity. The region’s massive natural gas infrastructure allows the potential for repurposing for clean hydrogen use rather than greenfield investments, which should lower costs and speed development. For exports, the use of hydrogen derivatives (liquid organic hydrogen carriers, ammonia, and methanol) can lower delivered costs versus liquid hydrogen.

The high cost of moving and storing hydrogen in a dedicated hydrogen network is another key challenge. Repurposing the current natural gas network may face technical and economic constraints. Permitting pipeline and storage facilities may face community opposition. Finally, safety concerns may trigger higher capital and operational costs to distribute hydrogen.

The hydrogen industry in the U.S. stands at a crossroads, with significant opportunities driven by federal incentives and growing infrastructure. The opportunities are prominent in Houston and Texas, given the competitive advantages in the region. However, meeting the ambitious goals of the next five years will require overcoming substantial regulatory and investment challenges.

The Hydrogen Technology Landscape

The U.S. Department of Energy (DOE) has set a target price of $1/kilogram (kg) for clean hydrogen. Blue hydrogen produced on the U.S. Gulf Coast can almost reach this target today, with a price between $1.10/kg to $1.50/kg, pending adaptation of new technologies for methane emission monitoring and control, and the partial oxidation or autothermal reforming technologies for methane or hydrocarbon conversion, with carbon capture and storage.

Existing technology can produce enough low carbon-intensity hydrogen to meet up to 25% of energy demand for future users. However, the cost must drop substantially to become competitive at scale. Further technological development is critical for producing clean hydrogen at an affordable price point. Monitoring systems must also be created to ensure that the produced hydrogen is indeed a low or zero-emission energy source. One of the ways that blue hydrogen produced from natural gas reforming can qualify for low-carbon credits is by using monitoring systems (satellites, LIDAR) similar to those used to certify low emissions from methane, a potent greenhouse gas. Conventional SMR will need to be modified or upgraded to include ATR and oxygen-blown partial oxidation, enabling a higher concentration of carbon dioxide to be captured from a single point to qualify.

Similar technologies can be implemented in refining and petrochemical facilities to decarbonize operations, with minimal investment in infrastructure. This would require building new carbon dioxide pipelines and developing additional subsurface storage sites while using existing technology and assets.

Green hydrogen produced by water electrolysis is expensive. Current costs range from $4/kg to $7/kg, making it critical to receive the subsidies of up to $3/kg included in the Clean Hydrogen Production Tax Credit of the 2022 Inflation Reduction Act. The cost is driven by the expensive metals, primarily platinum, used in the electrocatalysts employed with high current density Proton Exchange Membrane (PEM) systems, and the space and operational costs associated with alkaline electrolyzers. While most regions will face these challenges, Houston and the Texas Gulf Coast have a unique advantage of inexpensive and rapidly growing renewable electricity generation and a ready market for the monetization of the substantial amounts of co-produced oxygen during water electrolysis.

Fully meeting DOE targets will require reducing or eliminating platinum-group metals, as with the new anion exchange membrane technology, along with reducing the manufacturing costs to produce multiple units and leveraging low electricity prices. Figure 6 illustrates technological development pathways to meet these targets via electrolysis.

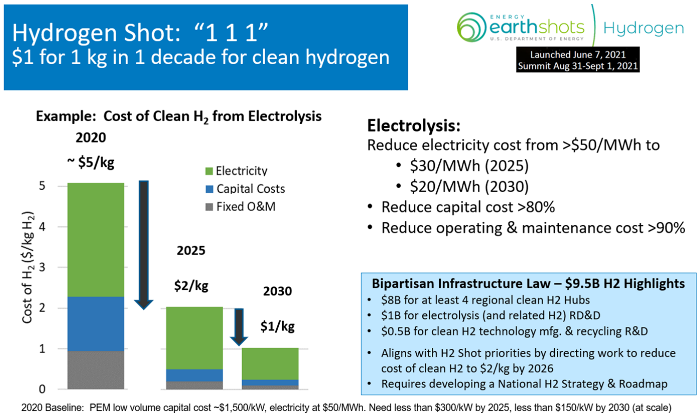

Figure 6. Technology pathway to $1/kg Green Hydrogen
Source: U.S. Department of Energy

The use of hydrogen in transportation is impeded by a similar issue with the scale-up of production costs associated with hydrogen fuel cells and their electrocatalysts. The cost and durability of fuel cell catalysts and components must improve if fuel cells are to be competitive with existing hydrocarbon-based fuels or battery-electric alternatives. Increased durability can be achieved at higher platinum loadings for electrocatalysts. However, that will increase the cost of production. Still, hydrogen-powered vehicles have simpler drivetrains than internal combustion engine vehicles, offering optimism for eventual economic parity.

Hydrogen fuel cell technology could also be a boon for decarbonizing marine transit, as could the conversion of clean hydrogen to ammonia. Ammonia cracking technology must be further developed to allow conversion back to hydrogen when it reaches the market.

While the Gulf Coast has ample storage options for carbon dioxide produced during the production of hydrogen from natural gas, access to sequestration sites is challenged due to concerns about its permanence and the consequent environmental challenges. Thermal decomposition of natural gas into hydrogen and solid carbon (methane pyrolysis, or "turquoise hydrogen") is being piloted in the Houston area for deployment in regions where storage is unavailable or where using solid carbon as a building material may be viable.

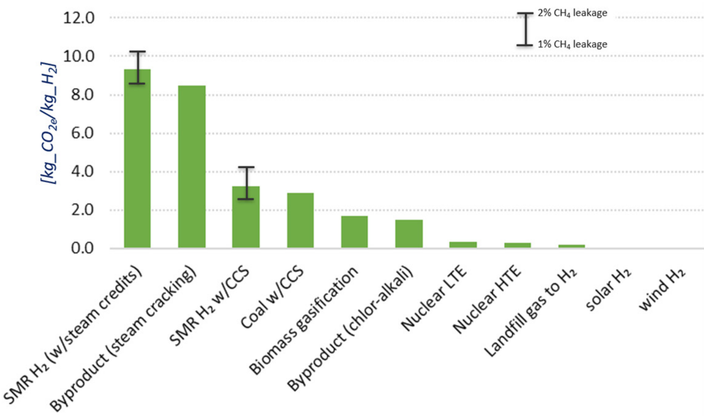

Figure 7. Carbon dioxide footprint of hydrogen production pathways. Error bars represent the range of carbon dioxide eq. emissions based on fugitive methane emissions upstream of the hydrogen production.
Source: U.S. Department of Energy, Argonne National Laboratory

As Figure 7 illustrates, nuclear energy, especially new, small modular reactors, offers game-changing possibilities to produce clean hydrogen, although costs remain high. The discovery of geologic hydrogen suggests another avenue. However, significant technology development is needed to understand where to look for existing pools of subsurface hydrogen and how it could be induced subsurface.

Industry stakeholders in the Houston region and elsewhere are examining these options, and collaborating on advancing energy storage, backup power, industrial decarbonization, and transportation decarbonization. However, additional policy support and clarification are needed to spur widespread investment in technology development.

Safety, Policies, and Regulations

Currently, hydrogen is widely used in industrial applications. Its risks and hazards are well understood, with techniques developed to mitigate those risks. However, a general lack of public understanding about hydrogen and its safe use could hinder the widespread adoption of new uses and facilities.

Addressing the risks and ensuring the development of a safety culture surrounding hydrogen will be essential to a successful hydrogen economy. The driving principles of this safety culture include protecting lives and property as a moral obligation, understanding that safe operations make good business sense, protecting market participants from catastrophic losses, and boosting efficiency and productivity.

Background

Hydrogen is the lightest element and has a gas density of approximately 0.07 kg/m³ at room temperature and atmospheric pressure. This is much lower than the density of air at about 1.2 kg/m³. This can be advantageous as hydrogen typically rises rapidly through the atmosphere and disperses if released in the open. At the same time, even though hydrogen is non-toxic, it can displace oxygen in confined spaces, creating asphyxiation risks. Further, hydrogen clouds can form under some conditions, leading to explosions. The broad flammability range of hydrogen in air, which is 5 to 75% as compared to 5 to 20% for natural gas and 3 to 10% for LPG, along with a significantly higher burning velocity than natural gas and LPG, can lead to explosive overpressure when hydrogen is confined. This can result in fires if hydrogen leaks into a confined space or is discharged horizontally at high velocity.

Notable historic incidents include:

- Manchester Township, New Jersey, 1937: The hydrogen-filled Hindenburg airship caught fire and was destroyed during an attempt to dock, resulting in 35 fatalities.

- Jackass Flats, Nevada, 1964: Hydrogen from a rocket vent ignited after 13 seconds in an unconfined area during a test to measure acoustic noise due to the high flow rate of hydrogen. The resulting explosion was heard 3.2 kilometers away, causing widespread but relatively minor damage.

- Sarnia, Canada, 1984: A hydrogen explosion and fire in the benzene unit of a petrochemical plant resulted in two deaths and two injuries. The explosion occurred when the unit was restarted following a scheduled maintenance shutdown.

However, over the last fifty years, the predominant cause of the over 200 incidents in the U.S. involving hydrogen has been attributed to human error. Nevertheless, hydrogen poses unique challenges as it is prone to leak from equipment and piping due to its extremely small molecular size. Leakage can occur through defective seals or fittings, or due to hydrogen embrittlement. In this process, hydrogen atoms diffuse and dissolve into a metal, reducing its ductility or toughness. Over time this can lead to cracking of the metal.

It can be difficult to identify leaks. Research is being conducted on odorizing hydrogen to address this problem. However, no viable odorizing solution has been identified.

Mitigation of Risks

Technological measures have been developed to mitigate the risks, including advanced seals to prevent leaks, vent systems to prevent build-up in confined spaces, criteria for selecting construction materials, and spacing guidelines for equipment.

In addition, best practices can further mitigate risks. These include:

- Incident Learning: Sharing lessons from past incidents is essential for improving safety.
- Safety Culture: A strong safety culture is vital, starting with thorough planning and preparedness.
- First Responder Training: Providing detailed incident information and training first responders are critical steps.
- Community Engagement: Educating the community on hydrogen safety and emergency procedures strengthens overall safety.
- Adhere to Standards: Following established safety codes and standards ensures compliance and enhances safety.

One of the unique features of the upcoming expansion of the hydrogen economy, at least in the short term, is that the primary source of interaction of the broad public with the hydrogen economy will be through the hydrogen pipelines and distribution systems that will deliver the produced hydrogen to their eventual end use in industry or transportation.

Hydrogen Pipelines – Safety and Regulation

The U.S. currently has about 1,600 miles of hydrogen pipelines[vi] mostly in Texas and Louisiana. There are also significant sub-surface (salt cavern) storage facilities in both states.

This network is poised for growth, which may include repurposing natural gas pipelines for hydrogen transport and transporting blended streams of natural gas and hydrogen. Regulations already cover hydrogen as a product and changing commodities in a pipeline. However, current regulations lack clarity on repurposing natural gas pipelines and blending requirements specifically for hydrogen – e.g., the maximum percentage of hydrogen allowed in the blend. The Pipeline and Hazardous Materials Safety Administration (PHMSA) has regulatory and safety oversight of hydrogen pipelines, including those in Texas.

In the absence of detailed hydrogen pipeline regulations, the industry relies on voluntary Recommended Practices (RPs) from the American Petroleum Institute (API). The RPs provide guidance in pipeline design and operation. API RP 1173 is a 10-part framework encompassing leadership commitment to safety, risk management, operational controls, management review, incident investigation, learnings, and documentation. These components minimize the number and severity of incidents, drawing from the "Swiss cheese model" of risk and accident causation. This likens safety systems to multiple slices of Swiss cheese, with randomly placed and sized holes in each slice. Each slice or layer represents a layer of defense against hazards and accidents, and the holes represent vulnerabilities within the layers. As long as the holes do not align with one another, an accident can be averted.

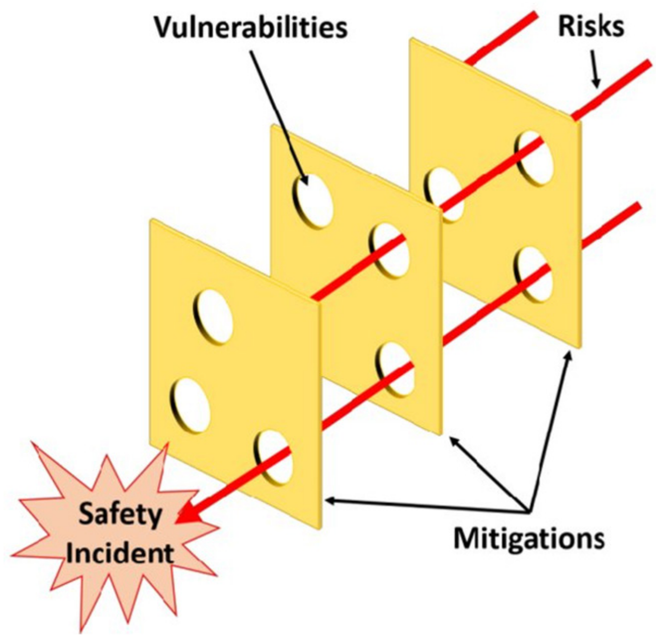

Figure 8. The Swiss Cheese Model
Source: Hopcraft et al. 2023[vii]

National Hydrogen Specific Codes[78]

- NFPA 2 Hydrogen Technologies Codes
- NFPA 30A Motor Fuel Dispensing Facilties and Repair Garages
- NFPA 55 Compressed Gases and Cryogenic Fluids Code

Component Design Standards

- ASME Boiler and Pressure Vessel[79]
- ASME B31.12-Hydrogen Piping and Pipelines
- ASME B31.1-Power Piping
- ASME B31.8-Gas Transmission and Distribution Piping Systems
- ASME B31.8S-Managing Systems Integrity of Gas Pipelines
- ASME B31.3-Process Piping
- CGA S-1.1-3: Pressure Relief Device Standards
- CGA-G-5.5: Hydrogen Vent Systems
- SAE J2600-Compressed Hydrogen Surface Vehicle Fueling Connection Devices
- UL 2075-Standard for Gas and Vapor Detectors and Sensors
- NFPA 77 and API RP 2003 offer guidance on grounding and static electricity

Model Codes

- International Fire Code
- International Building Code

Component Listing and Design Standards

Currently, few existing components are tested to listing standards implemented by a nationally recognized testing laboratory (NRTL). AHJs may allow the station manufacturer to provide technical information to prove that the compression, storage, and dispensing components used are fit for service. As the market develops, the list of listed components (and systems) is expected to grow.

Station Developer Standards (For informational use)

- SAE J2601-Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles[80]
- SAE J2799-Hydrogen Surface Vehicle to Station Communications Hardware and Software
- SAE J2719-Hydrogen Fuel Quality for Fuel Cell Vehicles
- HGV CSA Series Standards (currently being updated)

A second recommended practice, API RP 1163, provides recommendations for enhanced public awareness programs. This voluntary approach has enhanced safety without lengthy regulatory processes, reflecting a fundamental shift in how industry and regulators view safety and community engagement, favoring preemptive measures over regulatory compulsion.

Regulations are in place to ensure safety. They are created in response to a major safety incident or can be in response to research that shows a need to change standard designs or operating practices. For hydrogen pipelines, metallurgy is a key ongoing research area. It can address the unique problems of hydrogen-induced metal embrittlement that directly impacts the confinement efficacy.

There have been relatively few significant problems related to hydrogen pipeline maintenance or equipment failures in recent years, suggesting the current voluntary system is effective, at least insofar as the current business model for hydrogen and its transportation. However, as the hydrogen pipeline system expands, new regulations will be required to account for hydrogen's unique characteristics, such as susceptibility to embrittlement, metal cracking, and vulnerability to leakage. Future regulations could address:

- Minimum standard specifications for new pipelines to carry hydrogen or hydrogen blends.
- Repurposing existing natural gas pipelines for hydrogen service or hydrogen blends. The characteristics that should be considered for these regulations would include blend ratios, operating pressure, pipeline metallurgy, pipeline age and quality, and installation of leak detection.

An additional issue when repurposing pipelines is the agreements between pipeline operators and landowners. Agreements typically specify the commodity to be transported in the pipeline and may have to be renegotiated when the pipeline is repurposed to carry hydrogen or a hydrogen blend. There may be separate agreements for underground mineral rights. New initiatives will be crucial for safety as the industry expands the pipeline network.

Stakeholder Roles

In the U.S. several specialized organizations focus on hydrogen safety, including the Center for Hydrogen Safety (CHS) and the Hydrogen Safety Panel. CHS provides a range of training programs and information, including a first responders course, recorded webinars, e-learning courses that provide fundamental credentials, laboratory training, an electrolyzer safety course, and conferences for hydrogen professionals. Their website serves as a comprehensive online hydrogen safety resource. CHS also fosters a global community of experts sharing best practices in hydrogen safety.

The Hydrogen Safety Panel is a non-regulatory panel of professionals dedicated to industry safety. It provides guidance to help developers and project managers arrive at better solutions. The panel works across the project lifecycle, including the pre-project environment, early design, operations, and program support.

Hydrogen Policies in the U.S. and Texas

Policy at the national level is an important driver for developing the hydrogen ecosystem. Two key pieces of legislation are:

- The Infrastructure Investment and Jobs Act of 2021 (IIJA) includes significant funding for "regional clean hydrogen hubs."
- The Inflation Reduction Act of 2022 (IRA) includes production tax credits (PTCs) for various forms of clean energy. PTCs are based on the quantity of products produced and differ from ITCs, or investment tax credits, where the tax credit offsets a portion of the initial investment.

45V: Clean Hydrogen Production Tax Credit

- Provides tax credits for 10 years for projects operational before 2033.
- Defines "clean hydrogen" and outlines the criteria for qualifying.
- Projects are required to promote good-paying jobs by following prevailing wage standards and apprenticeship requirements to receive full credit.
- The carbon intensity calculation must use GREET – a suite of computational models developed and maintained by Argonne National Laboratory.

The most prominent credit for hydrogen is the 45V clean hydrogen production tax credit under the federal tax code. Tax credits for adjacent businesses including nuclear electricity (45U), CCUS (Carbon Capture, Utilization & Storage) (45Q), clean electricity (45Y and 48E), and advanced energy projects (48C) provide additional incentives for the clean hydrogen economy. 45V tax credits are given based on the carbon intensity (CI) of the hydrogen that is produced, as shown in Table 1 below:

Table 1. Tax credits under 45V based on carbon intensity.

Carbon Intensity kg CO_2e per kg of H_2	**Tax Credit** $/kg of hydrogen
< 0.45	3.00
0.45 - 1.5	1.00
0.15 - 2.5	0.75
2.5 - 4.0	0.60

The rulemaking process for 45V is not yet complete, and there is uncertainty about which projects will be able to use the credits and how large the benefits will be. The credits depend on the greenhouse gas emissions associated with each new hydrogen production facility, as determined by the GREET Model, (Greenhouse gases, Regulated Emissions, and Energy Use in Technologies), which is a full life-cycle model sponsored by the Argonne National Laboratory (ANL) for the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (Additional details are in the following section). One major area of contention is the way methane (natural gas) emissions are handled in the model for blue hydrogen projects. The version of GREET used for the calculations assumes a fixed percentage leakage of the natural gas supplied for hydrogen production and does not allow this percentage to be reduced for systems with lower leakage rates.

There are additional requirements for the 45V production tax credit. Most notably, for green hydrogen (i.e., hydrogen produced by electrolysis using electricity from renewable sources), the IRA specifies three main criteria:

- Time matching between renewable power and hydrogen production. By 2028, there must be hourly time matching between renewable electricity generation and hydrogen production.
- The renewables must be produced in the same region as the hydrogen.
- The power facilities need to be incrementally built within the same period as the hydrogen production facilities.

Adjacent Tax Incentives

45Y: Production tax credit for facilities generating clean electricity.

45U: Production tax credit for qualified facilities producing nuclear electricity.

45Q: Tax credit for geological storage or productive utilization of carbon dioxide and certain other carbon-based compounds.

48E: Investment tax credit for clean electricity projects.

48C: Tax credit for investments in advanced energy projects.

The 45Q tax credit for carbon sequestration was updated under IRA. The credit is now $180/ton for geologically sequestered carbon dioxide and $130/ton for captured carbon dioxide used in enhanced oil recovery or other purposes. With these increased credits, some blue hydrogen projects would be more attractive claiming 45Q credits rather than 45V production tax credits. Projects cannot claim 45V and 45Q credits at the same time. Paradoxically, in contrast, there are situations where projects can claim both 45V credits and 45Y credits.

State-level policies in Texas for hydrogen are ambiguous. The 88th session of the Texas Legislature in 2023 produced bills that favored fossil fuels and made renewable energy projects more difficult to implement. However, the Texas Railroad Commission, which oversees oil and gas operations in the state, created a new Hydrogen Production Policy Council, tasked with developing regulations to bolster the hydrogen market in Texas. This could help accelerate hydrogen infrastructure projects. In addition, legislation incentivized the adoption of clean emission vehicles, specifically hydrogen-powered heavy-duty trucks, with an annual budget of $8 million.

Likely topics for consideration in the legislative session that begins in January 2025 include the integration of dispatchable generation and small nuclear grid generation, management of water resources, and incentivization of innovative energy resources, including hydrogen. While the deployment of new carbon sequestration projects is largely stymied in Texas due to permitting roadblocks and backlogs, the impacts are likely to significantly impact the broader hydrogen economy.

There is also community resistance to new hydrogen and CCUS projects in some locations. This is often because of a lack of understanding about hydrogen technology. Previous safety incidents can significantly impact community perceptions. Communication and community engagement are essential to move forward, as is transparency between project operators, regulators, first responders, and the community.

Life Cycle Analysis (LCA) and Tax Credits

LCAs measure a product or service's cradle-to-grave environmental, economic, and social impacts. In the context of hydrogen, the most prominent application of LCAs is determining greenhouse gas emissions.

The GREET Model can be used to evaluate a range of energy systems, including petroleum, natural gas, wind, solar, and nuclear. The GREET model has about 60,000 users globally, in industry, academia, government, and other fields. Notably, GREET is used to inform policies and regulations, in the United States and beyond. The most relevant application of GREET for the current discussion is 45V, the Clean Hydrogen Production Credit.

Examples of GREET-informed Policies and Regulations

1. California’s Low-carbon Fuel Standard
2. Oregon’s Clean Fuels Program
3. Washington State Clean Fuel Regulation
4. U.S. Environmental Protection Agency for renewable fuel standard pathway evaluations
5. National Highway Traffic Safety Administration for fuel economy regulation
6. Federal Aviation Administration and International Civil Aviation Organization to evaluate aviation fuel pathways.
7. Canadian Clean Fuel Regulations by Environment and Climate Change Canada
8. Provisions of the 2021 Bipartisan Infrastructure Law and the 2022 Inflation Reduction Act, including 45Z (Clean Fuels Production Credit), 40B (Sustainable Aviation Fuel Credit), and 45V (Clean Hydrogen Production Credit)

There are several versions of GREET. R&D GREET[ix] gives users the flexibility to adjust parameters and thus to model and evaluate a wide range of feedstocks, configurations, and production systems, including emerging technologies, various types of water sources for electrolysis, and different geographical regions.

In contrast, GREET versions designed for regulatory purposes are more constrained. For example, in 45VH2-GREET (the version used for 45V evaluations), parameters within the model are categorized as either a) Foreground data with values that users must input to characterize well-to-gate emissions.Examples include the amount of electricity consumption onsite, rate of carbon capture, amount of feedstock consumption, and amount of hydrogen production, or b) Background data with fixed assumptions that may not be changed by the user. Examples include grid carbon intensity, counterfactual scenarios, and upstream methane emissions leakage.

ANL has evaluated numerous studies on hydrogen leakage from the supply chain. Based on these studies, the upstream methane leak rate associated with extracting, processing, and transporting natural gas is fixed at 0.9% in 45VH2-GREET.

45VH2-GREET can evaluate different pathways for hydrogen production, including SMR, ATR, low-temperature electrolysis, high-temperature electrolysis (nuclear), coal gasification, and biomass gasification.

The most potentially lucrative tier of 45V could allow producers in regions with cheap, plentiful, zero-carbon electricity to produce hydrogen almost for free as the capital costs of electrolyzers decrease.[x] At the same time, 45V must incentivize the production of hydrogen that is truly clean and enable the growth of a stable clean hydrogen market. The Clean Air Taskforce (CATF), an environmental organization, has advocated for this perspective and helped the Department of the Treasury in the rulemaking process for 45V. There are five main advocacy focuses for CATF, as outlined below.

1. Negative Emissions

ISSUE:

Some emissions accounting schemes allow for negative emissions from the use of biomethane.

Allowing such a system for 45V accounting could use taxpayer dollars to subsidize production methods that do not result in emissions reductions and could threaten the competitiveness of electrolytic hydrogen production.

PROPOSED SOLUTION:

Treasury's proposed regulation does not allow biomethane-based hydrogen production to count "negative emissions" in 45V carbon intensity calculations, although the Treasury department has opened this issue for comment. CATF continues to urge them to maintain the current guidance disallowing negative emissions accounting.

2. Fixed Upstream Leak Rates

ISSUE:

Under the current version of 45VH2-GREET, the upstream methane leak rate associated with extracting, processing, and transporting natural gas is fixed at 0.9%. The model also includes a fixed rate for upstream carbon dioxide.

PROPOSED SOLUTION:

Require use of the project-specific data that is submitted for subparts W and C of EPA's Greenhouse Gas Reporting Program (GHGRP).

This data, already submitted by most natural gas operators, is familiar to the EPA, and is verified by the built-in submission processes.

3. Emissions Averaging

ISSUE:

Annual averaging disproportionately penalizes hydrogen producers that must temporarily produce hydrogen with higher emissions intensity to maintain stable operations for customers.

PROPOSED SOLUTION:

Use a kilogram-by-kilogram approach to determine whether, and at what tier, hydrogen produced in a year qualifies for section 45V.

A two-step approach for determining lifecycle emissions:
1. An initial threshold of no more than 4 kg CO_2e/kg H_2 for all hydrogen produced.

2. Then calculate and credit each hour of hydrogen production from a facility separately.

4. Three Pillars for Electric Power

ISSUE:

Section 45V requires an evaluation of systemwide impacts when assessing lifecycle emissions.

Increased emissions can come from:
1. A lack of sufficient clean electricity to meet new demand from electrolyzers.

2. The use of electricity when clean resources are not producing.

3. The inability to deliver clean electricity to the electrolyzer.

PROPOSED SOLUTION:

Adopt a "three pillars" approach to limit the systemwide emissions from electrolytic hydrogen.

Producers must be required to purchase and retire Energy Attribute Certificates "EACs" that are generated:

1. From newly built clean electricity generators.

2. In the same hour as the hydrogen producer uses the electricity to produce hydrogen.

3. In the same region as the hydrogen production facility.

5. Exceptions to Incrementality

ISSUE:

A 5% exemption to incrementality is too broad and is contrary to the text and intention of Section 45V. A blanket exemption does not target the circumstances that cause curtailments, and unfairly allows financially healthy generators to be exempt when they do not need the hydrogen revenues to avoid retirement. Rhodium Group found that a 5% exemption could result in 1.5 billion metric tons of increased emissions cumulatively through 2035.

PROPOSED SOLUTION:

Adopt targeted compliance pathways for both curtailments and avoided retirements.

Curtailments: Treasury should establish price floors for the real-time price of electricity for the hydrogen producer (i.e., the locational marginal pricing), below which electricity could be considered curtailed.

Avoided retirements: A 5% allowance could be applied to facilities that prove that they are in financial distress and therefore need the section 45V tax credit to avoid retirement.

Community Engagement and Workforce Development

A portion of the federal government's $2 trillion investment in addressing climate change is earmarked for underserved communities. The Justice40 Initiative, included in Executive Order 14008, sets a goal for 40% of the overall benefits of certain federal climate, clean energy, affordable and sustainable housing, and other investments to flow to disadvantaged communities affected by underinvestment and pollution.

For the hydrogen economy, educating community members on hydrogen's role in the energy transition and removing barriers to their full participation in the hydrogen workforce will form the basis of meaningful community engagement and benefit, from all stakeholders, including federal and local government agencies, companies, and community organizations ranging from nonprofits to churches.

For most people, community engagement must start with learning about hydrogen, as the public is more familiar with other clean energy sources, including wind and solar. Simultaneously, to build trust, communities must be helped with identifying the needs and concerns of all members. Communities must also be empowered to communicate their needs regularly and effectively to other stakeholders in the hydrogen economy. Ultimately, meaningful community engagement will expand to understanding associated job opportunities and needed skills and create opportunities for the re-skilling or up-skilling that the workforce may need to participate and grow their careers.

The benefits of effective community engagement will go beyond jobs. Hydrogen projects can reduce the harmful emissions that have disproportionately impacted neighborhoods surrounding traditional refineries, petrochemical plants, and other energy projects. Converting heavy-duty vehicles to hydrogen fuel cell technology would also significantly reduce emissions.

The industrial stakeholders can benefit from community engagement based on more efficient decision-making, increased public buy-in for new facilities and operations, increased long-term viability, and reduced litigation. Traditionally, the industry has worked with local government agencies and mostly engaged with a handful of organized community groups. Engaging directly with all community members, starting early, and maintaining meaningful engagement for the long term will be new for some companies.

Outreach will involve multiple pathways:

- Information can be provided through public meetings, websites, brochures, and other communication venues.
- Focus groups, town hall meetings, and panel discussions allow for two-way communications, fostering relationships that can lead to collaboration.
- Digital communications allow companies, regulators, and others to reach a wider audience, but some underrepresented community members will need digital resources and literacy skills to access electronic communications.
- Investing in relationships with trusted community members can build the capacity for peer-to-peer education and training.
- Hiring from within the community can also help build trust and educate all members of the community about what a hydrogen project involves.

Building a Hydrogen Workforce

Workforce development enhances sector-specific skills, increases public awareness of the emerging opportunities in hydrogen energy, and produces community benefits. This is why effective and meaningful community engagement is tied to building a skilled hydrogen workforce.

The skills that will be needed are not completely new. Those who work in similar industries like energy, vehicles, and construction could transition to the hydrogen industry. More broadly, employers have expressed that they need a workforce with critical-thinking skills, high emotional intelligence, and the ability to work in teams.

In return, the hydrogen industry has an advantage that may serve to attract new talent. Given its role in decarbonizing the economy, many people, especially the younger incoming and future workforce, want to be a part of the solution to the climate change dilemma.

To effectively benefit underrepresented and disadvantaged communities, first and foremost, the skills that residents already have must be assessed. Some may need basic skills training, from reading and math to softer workplace readiness skills. Integrating life skills with technical skills training can build a more adaptable hydrogen workforce.

When assessing skills and developing community engagement and workforce development strategies, it is key to incorporate the needs of all stakeholders. For example, women and members of disadvantaged communities are less likely to apply for jobs if they do not have every requirement listed in the job description. This indicates that employers should consider job postings carefully and inclusively.

Retraining potential workers can happen at many venues including community colleges, training centers, and through apprenticeships, among other ways. Career programs in area high schools can help, bolstered by efforts to ensure that even young students and their families, are aware of the job opportunities in the hydrogen economy. Universities also have a role to play. This includes providing relevant four-year and graduate degree programs and working with industry to help them connect with local communities. Involving employers in reskilling efforts can ensure that workers have the needed skills and that employers better understand the people who will make up their future workforce. Several community-based organizations and non-profits are involved in sharing information about job opportunities, the skills and training required, and connecting community members with appropriate opportunities. All stakeholders, including project developers, government agencies, and educational institutions must work with these groups to increase the effectiveness of the workforce development efforts, build on the relationships that communities have with these organizations, and have these trusted community partners represent the needs and concerns of communities. As in other industries, reskilling and upskilling will not be a one-time effort. Providing people with the opportunities and ability to advance in their careers increases job satisfaction, lowers turnover, and can help address long-standing socioeconomic inequality in Houston.

The University of Houston's Role

The University of Houston, The Energy University®, offers several advantages. With its expertise in energy research and its strategic location on the Gulf Coast, UH can play play a vital role in supporting the growth of the hydrogen industry through:

- Technology research and development, particularly in areas like ammonia cracking, electrolysis and carbon capture efficiency improvements, and hydrogen transportation and storage solutions.
- Workforce development and training programs to build the skilled workforce needed to build and operate hydrogen facilities.
- Business and financial modeling to help structure viable projects and financing mechanisms.
- Opportunities for students and researchers to study the best methods of collaboration between all stakeholders.
- Foster collaborations among industry, government, community, and academic stakeholders to address regulatory/policy hurdles and environmental justice challenges.
- Independent, data-driven analysis to inform decision-making and public discourse around hydrogen.

Conclusions

Ambitious goals have been set for a decarbonized future, with a substantial role for hydrogen. Houston and the Gulf Coast have a generational opportunity to take a leading role in developing the global hydrogen industry for the energy transition. The regional concentration of heavy industry and already sector-leading hydrogen infrastructure places it ahead of other contenders. However, the region is not assured of maintaining this position without thoughtful and sustained efforts to increase collaboration and resolve the major challenges of the hydrogen economy.

The current Houston and Texas Gulf Coast hydrogen economy faces uncertainty about tax credits, delays in permits and equipment delivery, and other supply chain and logistics issues. These will result in pushing back projects. At the same time, current technologies are sufficient for meeting near-term hydrogen production goals. However, costs must be reduced significantly for large-scale production and to enable the hydrogen economy in the long term. Lastly, the current federal incentives and a regional hydrogen hub award present significant opportunities for the region to be a leader in hydrogen. The outlined goals cannot be met without solving the pressing regulatory and investment challenges ahead, and effective and meaningful community engagement and workforce development.

REFERENCES

[i] Houston as the epicenter of a global clean hydrogen hub. 2022. McKinsey & Company. https://www.mckinsey.com/~/media/mckinsey/business%20functions/sustainability/our%20insights/houston%20as%20the%20epicenter%20of%20a%20global%20clean%20hydrogen%20hub/houston-as-the-epicenter-of-a-global-clean-hydrogen-hub-vf.pdf

[ii] Houston: The Low-carbon energy Capital. Four Ways Forward. 2021. University of Houston. https://www.uh.edu/uh-energy-innovation/uh-energy/energy-symposium-series/2020-2021/low-carbon-energy-capital/content/uh-energy-houston-low-carbon-energy-capital-four-ways-forward.pdf

[iii] Hand E. Hidden hydrogen. Science. 2023 Feb 17;379(6633):630-636. doi: 10.1126/science.adh1477.

[iv] Global Hydrogen Flows: Hydrogen trade as a key enabler for efficient decarbonization. 2022. Hydrogen Council in collaboration with McKinsey & Company.

https://hydrogencouncil.com/wp-content/uploads/2022/10/Global-Hydrogen-Flows.pdf

[v] Section 45V of the federal tax code is a 10-year tax credit for clean hydrogen production. It can be worth up to $3 per kilogram of clean hydrogen produced, based on the carbon intensity, determined based on the lifecycle greenhouse gas emissions rate. For a more detailed discussion of 45V and other tax credits, see the section on Safety, Policies, and Regulations.

[vi] In comparison, there are about three million miles of natural gas pipelines in the U.S.

[vii] Hopcraft, R., Tam, K., Dorje Palbar Misas, J., Moara-Nkwe, K., & Jones, K. (2023). Developing a maritime cyber safety culture: Improving safety of operations.

[viii] H2Tools. 2024. H2Tools is intended for public use and was built, and is maintained, by the Pacific Northwest National Laboratory with funding from the DOE Office of Energy Efficiency and Renewable Energy's Hydrogen and Fuel Cell Technologies Office. https://h2tools.org/

[ix] GREET. 2024. Argonne National Laboratory's Systems Assessment Center.

https://greet.anl.gov/

[x] Han, H., Kent, E. 2023. Hydrogen in your Hulu ads: Here's why it matters. Clean Air Task Force.

https://www.catf.us/2023/12/hydrogen-hulu-ads-heres-why-it-matters/#:~:text=A%20key%20concern%20with%2045V,as%20electrolyzer%20capital%20costs%20decrease.

ABOUT UH ENERGY

UH Energy is an umbrella for efforts across the University of Houston to position the university as a strategic partner to the energy industry by producing trained workforce, strategic and technical leadership, research and development for needed innovations and new technologies.

That's why UH is THE ENERGY UNIVERSITY®.

ABOUT THE ENERGY TRANSITION INSTITUTE & TIEEP

Made possible by a $10 million gift from Shell, the Energy Transition Institute works to advance reliable, affordable, and environmentally responsible energy for all through a just and equity-driven pathway. With an emphasis on serving, educating and engaging underserved communities, the Institute focuses on three verticals: carbon management, hydrogen and circular plastics.

The Texas Industrial Energy Efficiency Program (TIEEP) assists Texas industries in maintaining their world-leading position through ever-improving energy intensity, reduced environmental impact, and enhanced social and economic development.

EDITORIAL BOARD

CONTRIBUTORS

713-743-5355
uhenergy@uh.edu
uh.edu/uh-energy-innovation/

UH Energy
UNIVERSITY OF **HOUSTON**

UH Energy
UNIVERSITY OF **HOUSTON**