HYDROGEN ENERGY DEVELOPMENT IN TEXAS

A Report for the 89th Texas Legislature
by the
Texas Hydrogen Production Policy Council

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TEXAS HYDROGEN PRODUCTION POLICY COUNCIL

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By the

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In 2023, the Texas Legislature created the Texas Hydrogen Production Policy Council (Council) to study and make recommendations relating to the policy framework of the Railroad Commission of Texas for hydrogen energy development in Texas. The Council was established in December 2023 pursuant to House Bill 2847 (88th Legislature, Regular Session), and its initial report details the Council's analysis and preliminary recommendations. The report's recommendations are focused on ensuring effective and consistent regulatory oversight of hydrogen production, transportation, and storage, while maximizing economic opportunities for the development of the hydrogen industry in Texas.

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Executive Summary

Texas is at the center of the world's energy industry, with an unparalleled combination of natural resources, infrastructure and human capital. These systemic advantages, developed over many decades, allow Texas to help meet the world's energy needs reliably, cost effectively, and at-scale. As the world's energy needs continue to expand, and as demand grows for clean[1] forms of energy, hydrogen has come into focus as one of the critical energy currencies of the future. As a global leader in conventional hydrogen production, Texas is well-positioned to maintain and expand its leadership as the hydrogen industry prepares for exponential growth over the coming decades.

The analysis and recommendations in this report are not exhaustive but are intended to present the next steps required to bolster Texas' national and global leadership in the hydrogen industry. Prudent regulation and guidance from the state government will allow Texas to capitalize on the economic and environmental opportunity in a safe and responsible way. Statutorily, the Council is planned to continue until January 1, 2030. Consequently, the recommendations and actions taken by the Council are expected to be continuously reviewed and modified as technologies, markets, and the regulatory landscape evolve.

In the first section, Regulatory Oversight, the Council summarizes the existing state and federal regulatory landscape governing safety, permitting, and environmental compliance across the hydrogen value chain. The Council's analysis of this regulatory landscape identifies areas with current oversight and areas wherein gaps may create the potential for improvement. While considering recommendations for change, the Council focused on:

- Safety: Confirming that existing statutes and rules ensure the safety of personnel working in the hydrogen industry, as well as the safety of the communities living in proximity to its infrastructure.
- Environmental Protection: Confirming that existing statutes and rules ensure the stewardship of Texas' natural resources and the protection of the environment.
- Regulatory Clarity and Efficiency: Ensuring that participants in the hydrogen industry face clear, consistent, and predictable regulatory requirements, while minimizing jurisdictional gaps or overlap.

In the second section, Maximizing the Economic Opportunity for Texas, the Council summarizes its study of the developing hydrogen industry. This analysis considers the potential economic opportunity presented by the hydrogen industry in Texas, evaluates the critical enablers of hydrogen industry development, and provides recommendations to remove barriers and accelerate this development in Texas. For ease of understanding, the Council has utilized the commonly labeled hydrogen production colors of hydrogen throughout the report. As discussed further in Appendix I, the Council recognizes that the more important focus should be on the carbon intensity (and not "color") of hydrogen. Colors refer to the many methods used to produce hydrogen (fuels, feedstocks and technologies), whereas

[1] As referenced throughout the report, "clean" hydrogen will refer to hydrogen that meets the U.S. DOE Clean Hydrogen Production Standard Guidance for low-carbon intensity hydrogen, which differs from the threshold for hydrogen production tax credits in the Inflation Reduction Act of 2022 (IRA), and in some contexts will also denote hydrogen's ability to reduce criteria air pollutants in certain applications.

"carbon intensity" refers to the resulting greenhouse gas emissions associated with the hydrogen produced, irrespective of method.

Texas Hydrogen Industry Growth Potential

Establishing Texas as the global center of the new hydrogen economy will provide significant, sustained, and strategic economic benefits to Texas in the years ahead. By 2050, Texas could see:

- Direct investment of $247 billion[2] for hydrogen industry and infrastructure development.
- Annual Texas hydrogen industry GDP of $100 billion.[3]
- The addition of 90,000[4] to greater than 180,000[5] jobs in the hydrogen industry.
- A renaissance in Texas manufacturing as new industries co-develop alongside clean, low-cost, reliable hydrogen supply. Industries such as renewable fuels, low carbon steel, ammonia and fertilizer, e-fuels and more.
- New demand of approximately 1 trillion standard cubic foot (scf) per year of natural gas and approximately 70,000 to 90,000 megawatts (MW) of electricity.[6]
- Storage of up to 56 million tons of CO_2 per year,[7] anchoring carbon capture and storage (CCS) industry development.
- Hydrogen solidifying Texas' position as the world energy leader by creating and providing pathways to leverage its existing refining, mid-stream and petrochemical assets.

The Council has summarized its key findings and recommendations below, focused both on regulatory oversight and maximizing the economic opportunity for Texas.

Regulatory Oversight

Finding 1: Regulatory oversight of the hydrogen industry is important to achieve primary priorities of safety and environmental stewardship and to ensure the hydrogen industry flourishes within the state.

The hydrogen industry can only be successful if it operates safely. Regulatory oversight must ensure worker safety for those constructing, operating, and maintaining hydrogen facilities and infrastructure. Careful attention must be paid to process safety to ensure that facilities operate without incidents. Likewise, regulatory oversight must ensure the hydrogen industry operates with a focus on environmental stewardship by protecting Texas' air and water quality. The hydrogen industry will only achieve its full potential for growth within the state if it maintains its focus on these key priorities.

Finding 2: Texas has a well-established, mature hydrogen industry for conventional hydrogen applications, having operated in the state for more than fifty years.

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[2] Baringa Partners, Hydrogen Council, Hydrogen in Decarbonized Energy Systems, p. 4.
[3] The Center for Houston's Future, Greater Houston Partnership, Houston as the Epicenter of a Global Clean Hydrogen Hub, p. 29.
[4] U.S. Department of Energy, https://www.energy.gov/articles/biden-harris-administration-announces-7-billion-americas-first-clean-hydrogen-hubs-driving (summary of direct, construction, and permanent jobs).
[5] The Center for Houston's Future, Greater Houston Partnership , Houston as the Epicenter of a Global Clean Hydrogen Hub, pg. 29.
[6] Assumes approximately 21 MTPA per CHF Report, one third Blue and two thirds Green per NPC report Exec summary, p. 40. Blue H2 assumes approximately 1/3 NG volume per volume of H2 produced. Green H2 assumes approximately 55 kwh/kg.
[7] Ibid (assumes 7 MTPA Blue H2) and 8 $kgCO_2e$ reduction per kg H_2 per NPC report Chapter 2, p. 15.

Although interest in hydrogen has recently risen, the hydrogen industry in Texas is well-established. Hydrogen has been in production for more than fifty years across dozens of facilities throughout the state. Pure hydrogen pipelines have been safely operating in Texas for years, with more than 1,000 miles of pure hydrogen pipelines in service today.[8] Several of the world's largest hydrogen storage facilities are operating in Texas, with more than 5 billion standard cubic feet of storage capacity in sub-surface salt caverns.[9] Texas is home to many of the largest consumers of hydrogen, including refiners and petrochemical producers, who actively consume 3.6 million tons of hydrogen annually.[10]

Finding 3: All aspects of Texas' existing conventional hydrogen industry—production, transportation, and storage—are already well-regulated. The introduction of new hydrogen production technologies, end-use applications, transport and storage technologies, and the involvement of new stakeholders in the hydrogen ecosystem warrants ongoing evaluation to ensure their proper integration into the regulatory framework.

The Council has systematically evaluated the existing oversight of the hydrogen industry, with a focus on safety and environmental stewardship. Oversight exists in multiple layers—federal, state and local—and covers the entire hydrogen value chain, including production, transportation, and storage. The Occupational Safety and Health Administration (OSHA) plays a central role in regulating worker safety and process safety in hydrogen production, with enforcement at the federal level. At the state level, the Texas Commission on Environmental Quality (TCEQ) oversees environmental regulations for hydrogen production, while the Railroad Commission of Texas (RRC) is responsible for the oversight of pipeline transportation and underground storage of hydrogen. Various other agencies also play a role regulating other areas of the hydrogen value chain, creating comprehensive oversight across the hydrogen industry.

Finding 4: Supported by the existing framework of regulatory oversight, Texas' hydrogen industry has maintained an exceptional record of safety and environmental stewardship throughout its many years of operation.

The hydrogen industry in Texas has operated for more than fifty years without major incident, supported by the oversight of the RRC, TCEQ, OSHA, and other regulatory agencies.

Finding 5: Hydrogen production occurs in various contexts, including refining, petrochemical, and other industries throughout the state. It is valuable to maintain consistent regulatory oversight across all sectors where hydrogen may be produced.

Hydrogen is produced as a co-product or intermediate in various industries, including oil refineries, fertilizer plants, and plastic production facilities. Therefore, maintaining a consistent regulatory framework across these industries is essential to prevent potential gaps and to minimize bureaucratic complexity.

Based on these findings, the Council makes the following recommendations to ensure proper regulatory oversight of the hydrogen industry in Texas:

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[8] National Petroleum Council, Harnessing Hydrogen, Chapter 3: LCI Hydrogen – Connecting Infrastructure, p. 43.
[9] Ibid, p. 41.
[10] The Center for Houston's Future, Greater Houston Partnership, Houston as the Epicenter of a Global Clean Hydrogen Hub, p.4.

Recommendation 1: Texas' state plan for hydrogen production oversight should maintain the current framework of regulatory oversight, with targeted clarifications and improvements.

The current regulatory framework has been effective in achieving the desired safety and environmental outcomes, efficient in its administrative process, and equal in its application across industries. While there are targeted areas that could use clarification or improvement (discussed in detail in Section 1, Part 2 below), the overall framework is sound and should largely remain unchanged.

Recommendation 2: Rulemaking should address hydrogen infrastructure, such as pipeline and casing materials, separately from infrastructure used for other products when distinction is technically merited based on hydrogen's unique physical properties.

While overarching safety and environmental regulatory frameworks should be consistent across industries, certain aspects of hydrogen's physical properties require special consideration. For example, when converting pipelines or sub-surface casings not originally engineered for hydrogen service, an analysis should be conducted to ensure proper material of construction for in-line components. Additionally, operational changes, such as reducing maximum operating pressure, may be necessary to mitigate risks like hydrogen embrittlement. Another area requiring attention is leak detection requirements, which should be guided by practical limitations in commercially available, field-tested technology for detecting hydrogen leaks.

Recommendation 3: Texas should identify hydrogen-focused individuals at relevant state agencies to improve the effectiveness and efficiency of oversight in hydrogen applications.

The state should identify state-level, centralized points of contact who are specialized in hydrogen and can serve as a hydrogen reference. For example, identifying a hydrogen-focused individual at the RRC who can provide guidance regarding hydrogen matters within the RRC's jurisdiction.

Recommendation 4: Training and education programs to improve public awareness of hydrogen, which will increase public acceptance of hydrogen and enhance safety, should be encouraged.

As the hydrogen economy grows, the use of hydrogen will become more common in non-industrial contexts, such as retail fueling or back-up power generation. Providing educational support, in collaboration with industry experts, to improve public awareness of hydrogen, communicate its risks, and demonstrate safe handling methods will help ensure public safety in these less-controlled contexts.

Recommendation 5: Texas should continue streamlining and standardizing its permitting processes.

Texas has an excellent track record of establishing and administering permitting processes that are consistent and efficient. With many permits required across numerous facets of the hydrogen industry (e.g., ERCOT interconnection approvals, RRC annual pipeline operating permits, TCEQ air permits, salt cavern storage development and operation, and future Class VI carbon underground storage permits), state and local agencies should continue to ensure permitting processes allow for safe operation and administrative clarity and efficiency. In other parts of the U.S., a lack of permitting clarity and efficiency is inhibiting the development of facilities and infrastructure needed for the hydrogen industry to expand. Texas has an opportunity to remain best-in-class in its permitting processes, positioning the state to maximize growth opportunities in the hydrogen sector.

Maximizing the Economic Opportunity for Texas

Finding 6: The growth of the hydrogen industry presents a major economic opportunity for Texas, with the potential to create new jobs, attract increased investment, and contribute to long-term GDP growth in the state.

The development of the hydrogen industry, along with its supporting infrastructure and its downstream markets within Texas, could attract billions of dollars of investment. This development may create hundreds of thousands of jobs and greatly boost the Texas economy.

Finding 7: Texas' hydrogen industry complements conventional energy production within the state by supporting the production of conventional and clean fuels and creating significant demand for natural gas and electricity production, bolstering Texas' position as a global energy leader.

Hydrogen supports the current energy economy in Texas as a critical component to both conventional refining and the growing production of new biofuels (such as renewable diesel and sustainable aviation fuel) within the state. As highlighted above, clean hydrogen production in Texas will create significant new demand for Texas energy, requiring approximately 1 trillion cubic feet per year of new natural gas and approximately 70,000 to 90,000 MW of new clean electricity generation by 2050.[11]

Finding 8: Rising demand for hydrogen will be driven by both existing and emerging markets, many of which have the potential to further improve Texas' economy and reinforce its status as a global leader in energy and manufacturing.

Beyond the opportunity to be the world leader in clean hydrogen production, Texas also has the opportunity to become a world leader in numerous high growth manufacturing sectors, such as renewable fuels, low carbon intensity steel, fertilizer, plastics, ammonia, methanol, LNG (using synthetic methane) and other products. With low-cost energy, robust multi modal freight mobility infrastructure, and access to global markets through world class ports, Texas has a potential to become a manufacturing center for the world, creating low-cost, low emission products that serve demand all over the globe.

Finding 9: Early investment in hydrogen infrastructure and development will grow hydrogen demand markets and should lead to reliable, lower cost, clean hydrogen, which can generate more demand, and, in turn, more investment and development, creating a positive feedback loop.

The regions that are first to develop world-scale infrastructure have a significant advantage and will naturally attract large new investments which seek the lowest cost, lowest risk, and highest potential for success. Larger networks of hydrogen production, demand, and interconnecting infrastructure drive higher reliability and lower cost, creating a cycle of growth for leading regions.

Finding 10: Texas is the current global leader in the hydrogen industry and can strengthen and further expand its leadership by supporting key enablers of hydrogen industry growth across the state.

Texas is a leader in nearly every dimension critical to the hydrogen industry, with low-cost natural gas, abundant and growing low carbon electricity, geology well suited for hydrogen and carbon storage,

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[11] Assumes 21 MTPA per CHF Report, one third Blue and two thirds Green per NPC report Exec summary, p. 33. Blue H2 assumes approximately 1/3 NG volume per volume of H2 produced. Green H2 assumes approximately 55 kwh/kg.

mature hydrogen demand centers, existing hydrogen pipelines, established port infrastructure, and more. By continuing to develop these advantages, Texas will expand its leadership position and become the global epicenter of hydrogen production.

Based on these findings, the Council makes the following recommendations to maximize the economic opportunity associated with hydrogen industry expansion in Texas:

Recommendation 6: Texas should continue to support its efforts to ensure a low-cost, reliable supply of natural gas and electricity, which are foundational to all forms of hydrogen production and to the industries creating hydrogen demand.

Ensuring electrical grid reliability and maintaining a world-leading low-cost profile for natural gas and electricity—particularly low carbon intensity electricity such as renewable, geothermal, or advanced nuclear—are foundational to the success of new projects. Existing natural gas and power transmission and distribution infrastructure will require continued investment and expansion to maintain reliable, low-cost supply while growing to meet new demand from hydrogen and other industries.

Recommendation 7: To promote the growth of clean hydrogen production derived from natural gas (commonly known as "blue" hydrogen), Texas should prioritize the development of carbon dioxide management infrastructure, including pipelines and underground storage, as well as expand the supply of lower emission natural gas, such as Responsibly Sourced Gas (RSG) and Renewable Natural Gas (RNG).

Blue hydrogen and blue hydrogen derivatives (e.g., ammonia) can be produced in Texas at scale and at a relatively low cost but can only develop as fast as the carbon capture and storage (CCS) infrastructure that supports them. Low emission natural gas, such as RSG and RNG, have the potential to increase the global competitiveness of Texas-sourced blue hydrogen, which will further increase global demand and Texas' potential as a global exporter of clean energy in the form of hydrogen and ammonia.

Recommendation 8: To support the expansion of clean hydrogen production through electrolysis (commonly known as "green" hydrogen), Texas should adopt an "all of the above" energy approach, encouraging the expansion of low carbon electricity production from existing sources (wind and solar) and emerging ones (nuclear and geothermal).

Texas has one of the strongest renewable electricity markets in the world, with rapid growth of low-cost electricity based on solar and wind production. In addition to continuing this positive momentum, additional development of clean power, especially in forms which are dispatchable (e.g., small modular nuclear and enhanced geothermal) will enable the growth of green hydrogen in Texas. Hydrogen could represent a grid-scale energy storage solution that can help support the increased development of renewable electricity from wind and solar. Renewable electricity that is converted to hydrogen can improve overall grid reliability, resilience and dispatchability.

Recommendation 9: Texas should encourage significant expansion of infrastructure supporting the entire hydrogen value chain, including:

(1) input energy infrastructure (e.g., electricity transmission and natural gas pipeline debottlenecking),
(2) hydrogen production infrastructure and facilities,

(3) *hydrogen transportation and storage infrastructure (e.g., hydrogen pipelines, underground storage, and ammonia terminals),*
(4) *supporting infrastructure (e.g., carbon dioxide pipelines and underground storage), and*
(5) *demand infrastructure (e.g., hydrogen fueling networks and manufacturing facilities consuming hydrogen).*

Wherever possible, this expansion should leverage existing infrastructure to minimize costs and environmental impact.

Infrastructure investment should be coordinated across all facets of the hydrogen value chain in parallel to ensure the production, transportation, storage, and consumption of hydrogen remain in balance throughout a period of significant expansion.

Recommendation 10: Texas' state policy to support the hydrogen industry should be designed to maximize economic benefits for its citizens while minimizing costs for taxpayers. This can be achieved by:

(1) *leveraging federal incentives, minimizing the need for state incentives,*
(2) *maintaining a business-friendly environment with efficient permitting processes and property tax abatements to support world scale, strategic projects,*
(3) *fostering industry development that creates hydrogen demand focusing on targeted, high impact end-uses, and*
(4) *aligning production with international standards, which will enhance Texas' potential as a global exporter of clean energy, hydrogen products and hydrogen derivatives.*

Significant federal incentives related to hydrogen are proposed that could provide billions of dollars of federal support alongside an even larger sum of private investment to projects developing in Texas. Texas has a strong history of supporting business growth through regulatory efficiency and consistency and strategic incentive structures. Texas should maintain this policy to support the key enablers of hydrogen industry growth. Likewise, similar support should be strategically directed to sectors that create hydrogen demand, such as clean steel, renewable fuels, sustainable aviation fuel, and clean ammonia facilities, as demand will ultimately set the pace of hydrogen industry growth. Texas should focus on fostering markets where hydrogen is advantaged over competing technologies and will support the largest and fastest growth potential, such as renewable fuels, ammonia, clean steel, and heavy mobility. Finally, Texas should consider the demand pull created by international policy (e.g., taxes, incentives, or mandates) by being aware of standards in international markets.

Next Steps

The hydrogen industry in Texas is positioned for significant growth in the coming years, driven by new and existing demand markets, and accelerated by the state's competitive advantages. The report that follows explores in detail the factors that position Texas to lead the nation in the development of hydrogen production and use. Factors that are a combination of:

- low-cost, abundant natural gas, low-cost, high capacity-factor wind, and solar resources,
- geology optimal for hydrogen and carbon storage,
- an administratively efficient regulatory and permitting environment,
- nation-leading pipeline infrastructure,
- a scaled workforce with hydrogen expertise and large project execution capability,

- deepwater port access to global markets,
- existing hydrogen demand centers, and
- billions of dollars in federal grants and tens of billions in potential federal tax credits.

Texas has every advantage to further develop its hydrogen economy. By maintaining the current regulatory framework for hydrogen production, transportation and storage, while supporting the critical enablers across the hydrogen value chain, Texas will expand its leadership position as the global epicenter of the hydrogen industry.

Section 1 – Regulatory Oversight

In the coming years, hydrogen's prevalence as an energy currency will grow in Texas and it is critical to ensure proper regulatory oversight over the production, transportation, and storage of hydrogen within the state. This oversight must prioritize a focus on safety and environmental stewardship, while maintaining an efficient and consistent system for permitting.

Finding 1: Regulatory oversight of the hydrogen industry is important to achieve primary priorities of safety and environmental stewardship and to ensure the hydrogen industry flourishes within the state.

Part 1 – The Current Regulatory Landscape

Finding 2: Texas has a well-established, mature hydrogen industry for conventional hydrogen applications, having operated in the state for more than fifty years.

Industrial-scale hydrogen production and transportation has existed in Texas for more fifty years. As a mature industry, regulatory oversight is already prevalent across the hydrogen value chain at federal, state, and local levels.

Finding 3: All aspects of Texas' existing conventional hydrogen industry—production, transportation, and storage—are already well-regulated. The introduction of new hydrogen production technologies, end-use applications, transport and storage technologies, and the involvement of new stakeholders in the hydrogen ecosystem warrant ongoing evaluation to ensure their proper integration into the regulatory framework.

I – Hydrogen Production Regulatory Oversight

The federal Occupational Safety and Health Administration (OSHA) provides primary regulatory oversight with respect to safety for the production of hydrogen in Texas.

OSHA's Construction[12] and General Industry[13] regulations provide the oversight with respect to worker safety at hydrogen production facilities. These standards are enforced at the federal level and cover a broad array of activities and conditions, ensuring safeguards for hazards to worker safety, such as:

- Working at heights (e.g., ladders, fall protection, scaffolding, falling-object protection)
- Emergency planning (e.g., exit routes, action plans)
- Vehicle safety (e.g., manlifts, moving platforms, cranes)
- Environmental controls (e.g., ventilation, confined space management)
- Management of hazardous materials
- Personal protective equipment (e.g., hard hats, hearing protection)
- First aid
- Fire protection (e.g., fire extinguishers, fire detection systems)
- Materials handling
- Machinery guarding
- Hand-held tools
- Welding, cutting, and brazing

[12] 1926 | Occupational Safety and Health Administration (osha.gov).
[13] 1910 | Occupational Safety and Health Administration (osha.gov).

- Electrical safety
- Toxic substance handling (e.g., lead, asbestos)
- Training requirements, and
- Other worker safety requirements

OSHA's standards create comprehensive requirements that are consistent across many industries, applying to hydrogen production in the same way they are applied in other large industrial contexts throughout the state.

OSHA's Process Safety Management of Highly Hazardous Chemicals standard (PSM)[14] provides the primary regulatory oversight with respect to process safety at hydrogen production facilities and is enforced at the federal level for hydrogen production facilities. The PSM standard applies to any hydrogen production facility with greater than 10,000 pounds of flammable gas or liquids and provides a rigorous framework to:

- Identify, document, and control process hazards
- Document equipment compliance with recognized and generally accepted good engineering practices
- Maintain safe operating procedures
- Ensure adequate, recurring training of employees
- Manage safety for contractors performing facility maintenance
- Require pre-startup safety reviews prior to activation of new or modified processes
- Ensure the mechanical integrity of process equipment, including required quality assurance, recurring inspection and testing, and correction of deficiencies for installed equipment
- Manage changes to equipment, procedures, or operating conditions
- Establish emergency action plans, and
- Implement additional safety requirements (managing hot work, investigate potential release incidents, etc.)

Strict adherence to PSM standard requirements is audited at each facility every three years, ensuring this framework maintains safe operation over the long term. For processes below the OSHA PSM threshold, additional OSHA requirements,[15] which incorporate code requirements from the American Society of Mechanical Engineers (ASME), the U.S. Department of Transportation (DOT), the American National Standards Institute, the National Fire Protection Association (NFPA), the American Petroleum Institute, the Compressed Gas Association, and other standards, ensure safe management of hydrogen in smaller systems.

The TCEQ, operating under delegated state-level authority from the federal Environmental Protection Agency (EPA), is the primary regulatory body responsible for overseeing environmental compliance in hydrogen production in Texas. The TCEQ issues and regulates air quality permits[16], ensuring that process vents, boilers, flares, cooling towers, process furnaces and other equipment are operated in manners to protect Texas' air quality. The TCEQ also regulates and issues water quality permits, overseeing the

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[14] OSHA, Process Safety Management - Overview | Occupational Safety and Health Administration (osha.gov).
[15] OSHA, 1910.103 - Hydrogen. | Occupational Safety and Health Administration (osha.gov).
[16] TCEQ, Air Permitting.

proper management of stormwater run-off[17] and the safe disposal of wastewater[18] generated at hydrogen facilities. The TCEQ also administers hazardous waste management[19] at hydrogen facilities, with authority delegated from the EPA under the Resource Conservation and Recovery Act (RCRA).

In addition to the environmental permits issued by the TCEQ, the new construction of hydrogen production facilities in Texas may require other federal, state, and local permits, which may vary depending on the location of the facility. For facilities impacting wetlands, the TCEQ and Army Corps of Engineers may be involved in permitting and mitigation approvals. The Texas General Land Office may be involved in coastal areas, and the Texas Parks and Wildlife Department has oversight with respect to wildlife habitats. Construction permits issued by local authorities provide further regulatory oversight for hydrogen production facilities.

In summary, the oversight of safety and environmental stewardship in hydrogen production is very similar to the oversight of many other large industries in Texas, such as refineries and petrochemical facilities. Federal, state and local regulations work together to ensure proper requirements are in place for the construction and operation of hydrogen production facilities in Texas.

II – Hydrogen Transportation Regulatory Oversight

Hydrogen transportation occurs in many forms, and the regulatory oversight varies across each method of transport: pipeline, truck or trailer, rail, ship or barge.

The RRC has primary regulatory oversight of the intrastate pipeline transportation of hydrogen in Texas.[20] In addition to permitting the operation of pipelines,[21] the RRC has jurisdiction over intrastate pipeline safety and enforces compliance with state and federal pipeline safety regulations. Currently, hydrogen pipelines are governed by the same regulations that apply to natural gas pipelines, which include requirements for:

- Pipeline design and material of construction
- Pipeline construction and fabrication (e.g., welding)
- Corrosion control requirements
- Pipeline testing requirements
- Pipeline operation
- Pipeline maintenance
- Personnel qualification
- Pipeline integrity assessment and management plans
- Documentation and retention of records
- Leak survey requirements
- Odorization
- Change of service or discontinuance of service, and
- Other regulatory requirements

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[17] TCEQ, Stormwater Permits.
[18] TCEQ, Wastewater and Stormwater.
[19] TCEQ, Industrial and Hazardous Waste.
[20] Texas Nat. Res. Code § 81.051 (5).
[21] 16 Tex. Admin. Code § 3.70.

The RRC audits pipeline operators to ensure rigorous compliance with requirements, ensuring safe long-term pipeline operation. Interstate pipeline transportation of hydrogen is governed by similar rules and enforced by the Pipeline and Hazardous Materials Safety Administration (PHMSA) at a federal level. In addition to overseeing pipeline safety, the RRC also oversees the application of common carrier pipeline statutes[22] in the state.

The Texas Department of Transportation (TxDOT) and Texas Department of Motor Vehicles (TxDMV) provide primary regulatory oversight with respect to the road transportation of hydrogen by truck or trailer. Hydrogen is primarily transported via road in the form of a cryogenic liquid or as a compressed gas. Liquid hydrogen, compressed gas trailers and hydrogen-fueled trucks must conform to TxDOT and TxDMV requirements. At the federal level, interstate road transport of hydrogen (considered a hazardous material) is governed by PHMSA[23] and enforced by the Federal Motor Carrier Safety Administration (FMCSA). Likewise, rail transportation of hydrogen is also governed by PHMSA[24] and enforced by the Federal Railroad Administration [25] (FRA). In the context of road or rail transportation, hydrogen oversight is managed similarly to other hazardous material transportation.

Hydrogen transportation over water via ship or barge is also governed with federal oversight from PHMSA[26], with engagement from the TCEQ while vessels are in berth, the U.S. Coast Guard during transit in harbor, and the International Maritime Organization while transporting overseas.

III – Hydrogen Storage Regulatory Oversight

Hydrogen storage also takes many forms: storage can occur subsurface (e.g., salt cavern, depleted oil and gas reservoirs) and at the surface in tanks or other storage vessels (e.g., ISO containers, tubes).

The RRC[27] provides primary regulatory oversight for underground storage of hydrogen in Texas, and the EPA[28] provides federal oversight as authorized by the Safe Drinking Water Act.[29] The RRC permits the development of both salt cavern storage[30] and depleted reservoir storage[31] within the state.

Similar to hydrogen production, surface storage of hydrogen in tanks and other vessels is subject to the same rigorous OSHA PSM standard requirements for storage installations greater than 10,000 pounds. Likewise, for smaller storage systems below the OSHA PSM threshold, additional OSHA requirements apply,[32] which incorporate code requirements from ASME, DOT, ANSI, NFPA, API, CGA, and other standards to ensure safe storage of hydrogen in smaller quantities.

[22] Tex. Nat. Res. Code, Ch. 111.
[23] 49 CFR Part 177 -- Carriage by Public Highway.
[24] 49 CFR Part 174 -- Carriage by Rail.
[25] Civil Penalties Schedules & Guidelines | FRA (dot.gov).
[26] 49 CFR Part 176 -- Carriage by Vessel.
[27] Tex. Nat. Res. Code § 81.051(5).
[28] Protecting Underground Sources of Drinking Water from Underground Injection (UIC), U.S. EPA.
[29] eCFR: 40 CFR Chapter I Subchapter D -- Water Programs.
[30] 16 Tex. Admin. Code § 3.97.
[31] 16 Tex. Admin. Code § 3.96.
[32] OSHA, 1910.103 – Hydrogen, Occupational Safety and Health Administration (osha.gov).

Part 2 – Assessing Existing Regulatory Oversight and Recommendations to Address Gaps

In assessing the current landscape of regulatory oversight for the hydrogen value chain, including production, transportation, and storage, several key themes and recommendations emerge.

While hydrogen has gained significant new attention in recent months, the hydrogen industry within the state of Texas is mature, and, in large part, experiences similar regulatory oversight to many other industries within the state. Having operated for more than half a century within the state, hydrogen production facilities and pure hydrogen pipelines are managed using industry best practices and have been governed by the same industry regulations and jurisdictional enforcement that is applied to adjacent industries throughout the state such as oil refineries, petrochemical facilities, natural gas pipelines, etc.

Finding 4: Supported by the existing framework of regulatory oversight, Texas' hydrogen industry has maintained an exceptional record of safety and environmental stewardship throughout its many years of operation.

In the midst of this oversight by OSHA, RRC, TCEQ, and the other agencies described above, the hydrogen industry within the state has maintained an exceptional record of safety and environmental stewardship, demonstrating that the existing oversight has been effective in achieving the intended results.

Finding 5: Hydrogen production occurs in various contexts, including refining, petrochemical, and other industries throughout the state. It is valuable to maintain consistent regulatory oversight across all sectors where hydrogen may be produced.

Recommendation 1: Texas' state plan for hydrogen production oversight should maintain the current framework of regulatory oversight, with targeted clarifications and improvements.

There is value in maintaining consistency in regulatory oversight between the hydrogen industry and other similar industries in the state. While hydrogen is often produced at industrial gas facilities solely dedicated to its production, it is also produced in various other industrial contexts as a byproduct of a different industrial process. For example, reforming units that produce hydrogen are frequently integrated into larger oil refinery operations. Large scale olefins production units (e.g., ethylene crackers) co-produce crude hydrogen off-gas, while ammonia and urea facilities serving fertilizer production create large quantities of hydrogen as precursors to their final products. Likewise, many newer direct-reduced iron (DRI) steel facility designs have integrated hydrogen production. Given the existing, widespread overlaps between these industries, introducing different regulatory oversight for hydrogen production in the industrial context would create an exceedingly complex administrative challenge. As the RRC, TCEQ, OSHA and other state and federal agencies already provide consistent and significant oversight in these industries, maintaining the current regulatory landscape is a sound strategy.

In Texas, a Class V UIC permit granted by the RRC is required prior to developing a salt cavern for hydrogen storage. Conversion of service to hydrogen or hydrogen blending applications for pipeline safety purposes will be addressed by PHMSA, and the RRC is required to adopt the federal minimum pipeline safety standards. PHMSA should create clear requirements that ensure risks associated with hydrogen's unique physical properties are properly managed. Hydrogen is also produced outside of traditional industrial processes. Naturally occurring underground hydrogen ("white" hydrogen) and underground hydrogen generated in-situ ("gold" hydrogen) has many functional similarities to the upstream production of oil and gas. White and gold hydrogen will be regulated by the RRC, maintaining consistency with RRC's oversight of underground gas production, transportation and storage.

Finally, regulatory requirements should be crafted in a way that enables continued research and development supporting hydrogen industry growth. For example, ensuring that UIC Class VI permit applications using composite confinement continue to be evaluated for approval by the RRC enables research on porous media storage of hydrogen via Class V permits issued by the RRC, which could greatly expand the hydrogen storage potential within the state.

Recommendation 2: Rulemaking should address hydrogen infrastructure, such as pipeline and casing materials, separately from infrastructure used for other products when is technically merited based on hydrogen's unique physical properties.

While maintaining the existing framework of regulatory oversight provides a strong foundation, pipeline materials and pipeline safety rulemaking should treat hydrogen with distinction from other chemical materials where there is a technical justification to do so. Federal regulators and standards making bodies recognize the risk of corrosion mechanisms like hydrogen embrittlement in pipelines containing a high percentage of hydrogen and are working to incorporate this technical reality into pipeline rules. The ASME is in the process of merging elements from the ASME B31.12 Hydrogen Piping and Pipelines standard into its B31.8 Gas Transmission and Distribution Piping Systems standard. The 2018 ASME B31.8 is incorporated by reference into many critical PHMSA pipeline standards, the standard will likely apply to hydrogen pipelines.

Additionally, PHMSA has recently been discussing changes to Leak Detection and Repair (LDAR) rules.[33] Physical leak detection of hydrogen is much more challenging than that of natural gas (i.e., methane) as evidenced by the lack of commercially available technologies to detect hydrogen leaks in a field environment. Thus, any updates to LDAR rules should be made recognizing the technological differences between hydrogen and natural gas. While pipeline operators are required to notify the RRC upon a change of service, it is not mandatory to modify pipeline component materials of construction or alternatively reduce the maximum operating pressure to safely accommodate a conversion to hydrogen service. Experienced hydrogen pipeline operators within the state abide by industry best practices to ensure safe operation, but these best practices should be incorporated by reference into state and federal rules surrounding conversion of service. The RRC and other agencies with jurisdiction across the hydrogen value chain should incorporate rules that appropriately distinguish requirements for hydrogen service to ensure safe operation in these areas where hydrogen's physical properties warrant such a distinction. For example, the RRC should consider codifying limits on operating pressure to a lower percentage of SMYS (specified minimum yield strength) in service with a high percentage of hydrogen to minimize pipe stress below thresholds where hydrogen embrittlement is a concern. Likewise, for sub-surface storage of hydrogen, all wells within the Area of Review for a permit application should consider whether they will be exposed to hydrogen service and be appropriately designed and operated for that service.

[33] US DOT PHMSA, Pipeline Safety: Gas Pipeline Leak Detection and Repair.

Recommendation 3: Texas should identify hydrogen-focused individuals at relevant state agencies to improve the effectiveness and efficiency of oversight in hydrogen applications.

Creating centralized points of contact specialized in hydrogen at the state who can serve as resources to the public and industry is recommended. For example, a staff or office point of contact for hydrogen at the RRC could provide consistent guidance with respect to matters within the RRC's jurisdiction, or a point of contact at the Texas Department of Licensing and Regulation (TDLR) could provide consistent guidance with respect to hydrogen fueling infrastructure, providing codes and standards support.

Recommendation 4: Training and education programs to improve public awareness of hydrogen, which will increase public acceptance of hydrogen and enhance safety, should be encouraged.

While regulatory oversight is robust in the current industrial context, as the hydrogen economy grows, hydrogen will become much more ubiquitous and will see more engagement from individuals who are not well-trained in an increased number of locations and in retail environments (e.g., refueling stations). Prioritizing hydrogen training for the public will increase acceptance of hydrogen and enhance safety.

Recommendation 5: Texas should continue streamlining and standardizing its permitting processes.

Texas' emphasis on efficient permitting processes has historically been a strength, attracting development that has often avoided states burdened by excessive bureaucracy or prolonged permit timelines. Texas can continue to be a leader in this regard by continuing to prioritize permits related to hydrogen production, transportation and storage, as well as permits for critical upstream supply chains and downstream demand centers.

Once the EPA approves RRC's application for primary authority over the UIC Class VI (underground carbon storage) Program, there will be a single permitting authority, which will significantly improve the efficiency of permitting for infrastructure critical for blue hydrogen development within the state. Continuing to reduce electrical interconnection permit timelines is essential to support the growth of green hydrogen development. Construction permitting and environmental permits—such as TCEQ air permits—are frequently a critical path for development of both hydrogen production facilities and those creating hydrogen demand, such as DRI (direct-reduced) iron steel facilities, low-emission olefins facilities and renewable diesel hydrotreaters. Permit issuance for the operation of hydrogen pipelines, historically managed effectively and efficiently by the RRC, will remain critical as these pipelines develop more rapidly in the years ahead.

Section 2 – Maximizing the Economic Opportunity for Texas

Part 1 – The Clean Hydrogen Economic Opportunity

As global energy consumption grows and demand for cleaner forms of energy accelerates, the clean hydrogen industry is positioned for immense growth. Global hydrogen demand has a potential to grow 4.5 times, from 95 metric tons per annum (MTPA) to 430 MTPA, with greater than 95 percent produced as clean hydrogen by 2050.[34] With favorable policies and access to natural resources, the U.S. hydrogen industry could grow even more dramatically, with a potential to expand 5 to 7.5 times in the same

[34] International Energy Agency, Net Zero Roadmap 2023 Update, p. 101.

period, from 11 MTPA to 50-75 MTPA.[35,36] More than half of this growth (40 MTPA) is expected to be in the U.S. Gulf Coast,[37] with Texas positioned to produce approximately 4 percent of global hydrogen demand – 21 MTPA,[38] up nearly 5 times from 3.6 MTPA today.[39] Putting this into perspective, in 2023 Texas had a record year for oil and gas production, producing 5 percent of global oil and 8 percent of global gas,[40,41,42] and the potential for hydrogen industry leadership could extend Texas' tradition of energy dominance far into the future.

Finding 6: The growth of the hydrogen industry presents a major economic opportunity for Texas, with the potential to create new jobs, attract increased investment, and contribute to long-term GDP growth in the state.

Finding 7: Texas' hydrogen industry complements conventional energy production within the state by supporting the production of conventional and clean fuels and creating significant demand for natural gas and electricity production, bolstering Texas' position as a global energy leader.

The growth of the hydrogen industry presents a significant economic opportunity for the state of Texas. By 2050, the hydrogen industry is anticipated to contribute $100 billion annually[43] to the Texas GDP, creating over 180,000 new jobs.[44] This significant market growth will require an investment of $247 billion[45] in new hydrogen infrastructure in Texas. These impacts could be much larger, as they do not encompass the jobs, investment, and GDP growth driven by the numerous downstream markets enabled by the hydrogen industry development – clean steel, renewable diesel, sustainable aviation fuel, e-fuels and clean chemicals, and other markets described further in this report. These economic impacts also do not incorporate the significant increase in primary energy feeding the hydrogen facilities, which could represent an additional demand of nearly approximately 1 trillion cubic feet per year of natural gas and approximately 70,000 to 90,000 MW of new clean electricity generation by 2050.[46] Additionally, the hydrogen industry is positioned to anchor the development of carbon management in the state, with a potential to sequester up to 56 million tons of CO_2 per year.[47] Combined, the growth in hydrogen supply, input energy, and downstream demand represents a renaissance in clean energy and manufacturing, driving the Texas economy for decades to come.

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[35] U.S. DOE, U.S. National Clean Hydrogen Strategy and Roadmap, p. 13.
[36] National Petroleum Council, Harnessing Hydrogen, Report Summary, p. 28.
[37] National Petroleum Council, Harnessing Hydrogen, Report Summary, p. 29.
[38] The Center for Houston's Future, Greater Houston Partnership, Houston as the Epicenter of a Global Clean Hydrogen Hub, p. 20.
[39] The Center for Houston's Future, Greater Houston Partnership, Houston as the Epicenter of a Global Clean Hydrogen Hub, p.4.
[40] Railroad Commission of Texas, Texas Oil and Gas Production Hit Record Highs in 2023.
[41] U.S. EIA, Four countries could account for most near-term petroleum liquids supply growth.
[42] Statista, Natural Gas Production Worldwide from 1998 to 2023.
[43] The Center for Houston's Future, Greater Houston Partnership , Houston as the Epicenter of a Global Clean Hydrogen Hub, p. 29.
[44] Ibid. 45.
[45] Baringa Partners, Hydrogen Council , Hydrogen in Decarbonized Energy Systems, p. 4.
[46] Assumes 21 MTPA per CHF Report, one third Blue and two thirds Green per NPC report Exec summary, p. 33. Blue H2 assumes approximately 1/3 NG volume per volume of H2 produced. Green H2 assumes approximately 55 kwh/kg.
[47] Ibid (assumes 7 MTPA Blue H2) and 8 $kgCO_2e$ reduction per kg H_2 per NPC report Chapter 2, p. 15.

Part 2 – The Industries Driving Hydrogen Demand Growth

Hydrogen's versatility as an energy currency makes it foundational to a myriad of existing and new industries, many of which are themselves poised for immense growth over the next few decades.

Finding 8: Rising demand for hydrogen will be driven by both existing and emerging markets, many of which have the potential to further improve Texas' economy and reinforce its status as a global leader in energy and manufacturing.

I – Hydrogen Use as a Chemical Feedstock

Historically, hydrogen demand has been driven by its use as a chemical feedstock within the refining (hydrotreating and hydrocracking) and petrochemical (ammonia and methanol) industries where there is no viable alternative to hydrogen supply. Hydrogen will continue to be critical to these well-established industries, but much of the growth potential for hydrogen's use as a feedstock is expected to come from new industries. Biofuels like renewable diesel (RD) and sustainable aviation fuel (SAF) use clean hydrogen for hydrotreating and hydrogenation. Likewise, hydrogen can be used to pre-treat pyrolysis oil prior to reuse in circular plastic production. DRI (direct-reduced iron) processes use clean hydrogen in clean steel production at-scale in lieu of traditional blast furnaces. E-Fuels and 'Power-to-X' applications create synthetic hydrocarbons by combining clean hydrogen and carbon dioxide (CO_2), creating 'drop-in ready' clean gasoline, jet fuel, methanol, methane and other petrochemical precursors.

II – Hydrogen Conversion into Hydrogen Derivatives or Chemical Carriers

Hydrogen derivatives (also described as chemical carriers) are poised to enable global export of clean energy by converting hydrogen into ammonia, methanol, e-methane and other hydrogen containing compounds, e.g., Liquid Organic Hydrogen Carriers (LOHC) such as toluene. Ammonia-based fertilizer production is a significant existing demand market for hydrogen today. A large portion of future growth in the ammonia market is expected to consume clean hydrogen to produce clean ammonia. Clean ammonia and methanol can be utilized as low emission bunker fuel alternatives for at-scale global shipping. Ammonia as a hydrogen derivative can be a versatile energy export, shipped globally and used directly as a petrochemical feedstock, co-fired into coal-fired power facilities, or dissociated back into hydrogen for use in an overseas market. E-methane can be synthesized (using clean hydrogen and captured carbon dioxide) and used as clean LNG that reduces emissions while utilizing the existing assets in the LNG supply chain.

III – Hydrogen Use in Power Production

Hydrogen has numerous potential applications in the power market. Clean hydrogen can be co-fired into natural gas turbines to reduce emissions in existing natural gas power facilities, and as described above, clean ammonia can be co-fired at coal-fired power facilities. With significant progress in hydrogen fuel-cell, turbine and engine development, 100 percent hydrogen-fueled power generation applications present significant potential as a dispatchable form of clean power. Combined with at-scale, underground storage (e.g., in a salt cavern), hydrogen is one of the lowest cost strategies to enable long-term, grid-scale, seasonal power storage. Clean hydrogen can be produced during periods of excess power supply, stored in a salt cavern, and dispatched for power production during periods of elevated power demand. This strategy makes clean hydrogen an excellent complement to smooth out the supply/demand imbalances from volatile renewable power production. Hydrogen fuel cells represent an alternative to diesel generators in backup power applications and have been utilized for primary or backup power in numerous high reliability applications such as powering data centers, which represent a significant new demand market for reliable, clean, dispatchable power.

IV – Hydrogen Use in Mobility Applications

Hydrogen can be used directly as a fuel in numerous mobility applications. Hydrogen is often best suited for heavy transport clean fuel applications where battery weight, range and recharge durations become impractical for vehicles such as buses, trucks, ferries, trains and other heavy machinery (e.g., mining trucks, construction vehicles, etc.). The lack of emissions make hydrogen an excellent fuel for indoor material handling applications, such as forklifts in warehouses, especially in locations where high utilization favors hydrogen's quick refueling capabilities over battery alternatives and where combustion engine forklifts are not allowed (e.g., warehouses for food and drugs). Hydrogen contains the most energy per weight of any fuel, making it a mainstay in aerospace applications, where it has been utilized as rocket fuel for more than sixty years. Hydrogen's high energy density also makes it a primary focus for development as a jet fuel alternative for airplanes. While the demand in several of these mobility applications may take years to grow as new vehicle manufacturing ramps up, hydrogen's critical role supporting renewable diesel and SAF production (mentioned above) is already driving a significant demand increase in hydrogen today.

V – Hydrogen Use as a Fuel Alternative for High-Heat Applications

Hydrogen's use as a fuel alternative for high-heat applications provides even further opportunities for hydrogen demand growth. Industrial furnaces (e.g., cement production) and boilers can be fired using hydrogen fuel. In some petrochemical applications (e.g., olefin crackers), the potential to utilize hydrocarbon rich off-gas for blue hydrogen production, which can then be utilized to fuel the furnaces, presents a unique circular emissions reduction opportunity. Refineries can likewise reduce their emissions footprint by reforming their waste gases into blue hydrogen. In addition to greenfield industrial heat applications, with the appropriate metallurgical due diligence, hydrogen can be blended into existing fuel streams in retrofit applications to reduce emissions.

Part 3 – Hydrogen Performance Fundamentals, the Development Cycle, and Hydrogen Hubs

The simultaneous evolution of the markets discussed above provides a diverse and robust growth opportunity for hydrogen demand, which will develop in a cycle in regions like Texas that can establish and maintain early leadership in the hydrogen industry. In this positive feedback cycle, the expansion of industries consuming hydrogen enhances the overall performance of the hydrogen industry, which, in turn, accelerates demand growth. This cycle creates a reinforcing momentum where greater hydrogen adoption strengthens the industry's foundation, fostering further innovation, investment, and development. To understand this cycle, it is important to understand the core performance fundamentals of the hydrogen industry.

Finding 9: Early investment in hydrogen infrastructure and development will grow hydrogen demand markets and should lead to reliable, lower cost, clean hydrogen, which can generate more demand, and, in turn, more investment and development, creating a positive feedback loop.

While the hydrogen consuming industries demonstrate broad diversity, they each require three performance fundamentals from the hydrogen industry:

- Reliability of Supply
- Low-Cost Economics
- Low Carbon Intensity

Once achieved, these three performance fundamentals create a development cycle.

I – Reliability of Supply

Many industries that use hydrogen require a reliable supply to maintain economies of scale and steady utilization. These industries include renewable fuels production, clean steel production, ammonia/methanol production, petrochemical and refinery fuel switching, power production and global energy export. Unplanned shutdowns caused by supply disruptions can lead to costly downtime and ripple effects across global supply chains.

Additionally, many of these applications utilize hydrogen as a chemical feedstock or reagent, where the purity or quality of supply are crucial to avoid catalyst poisoning, which could result in costly downtime or unplanned replacement. Maintaining reliability at such a scale requires a combination of ample supply capacity, underlying operational excellence at each hydrogen production facility, and an infrastructure resilient to single points of failure throughout the hydrogen supply chain.

For large scale projects to succeed, developers must be confident that reliable supply is attainable, can be delivered on schedule, and will be sustained over the many decades required to secure a return on investment.

II – Low-Cost Economics

Large scale projects that need hydrogen for operation require competitive, low-cost economics to enable success. Large scale production must be combined with low-cost feedstocks and low-cost energy to achieve a cost-profile that can compete in global markets. Facilities with the lowest cost can ensure high utilization to meet global demand, while those with an expensive cost profile will swing as the marginal capacity in a global market, greatly reducing project economies of scale.

III – Low Carbon Intensity

The majority of growth in the hydrogen industry will require a third component: low carbon intensity. As global markets evolve for clean products, competitiveness in these markets will require a balance between economic viability and emissions reduction. Delivering hydrogen with low carbon intensity will maximize demand across global markets and allow producers to differentiate products with premium pricing. These attributes will position market leaders to attract consumers seeking to reduce the carbon intensity of their operations and secure incentives that enable project success in the near term.

IV – The Hydrogen Development Cycle

These three performance fundamentals—reliability, low cost, and low carbon intensity—can be challenging to attain, but once achieved, they become self-reinforcing, accelerating the development cycle. To begin the cycle, new demand industry megaprojects must be co-developed with numerous hydrogen production facilities and the necessary interconnecting infrastructure. Developing these projects as standalone ventures exposes hydrogen producers and off-takers to significant risks, including project schedule delays, facility capacity limitations, reliability issues and carbon intensity concerns. Clean energy and carbon dioxide management supply chains can also suffer from single points of failure, amplifying these risks. Many of these risks are greatest in the early years of production, when project returns are most vulnerable to erosion and incentives are most readily lost. Without synchronized development, both the producer and downstream customers face uncertainties that could undermine the long-term success of large-scale hydrogen projects.

However, once a hydrogen supply network is established, development improves in a self-reinforcing cycle, providing the following benefits:

- New offtake development is de-risked by the presence of at-scale, reliable, existing supply, which provides mitigations to project schedule, capacity, and reliability.
- New supply adds production capacity and infrastructure to the network, increasing resiliency and reducing the impact of any single point of failure on the system. This new production is often the most efficient and the lowest carbon intensity, providing opportunities to improve the cost profile and emissions footprint of the system over time.
- Multiple low emissions facilities create resiliency in the clean energy and/or carbon dioxide management infrastructure, further mitigating the likelihood of upset events that increase emissions intensity.
- Increased demand density creates a competitive supply environment, where multiple pipelines provide both an inherently more resilient, and simultaneously lower cost hydrogen supply.

Once the hydrogen network reaches a critical scale, market liquidity improves, leading to improvements in economics and opportunities to maximize asset value. The availability of spot supply and optionality to optimize the cost and carbon intensity of hydrogen supply in real time provides developers with greater operational efficiency and risk mitigation. This type of resilient, low-cost, low carbon intensity, liquid market is a preferred choice for new developers as opposed to a standalone supply alternative, which continues the cycle. As the market expands and matures, it attracts more investment, perpetuating growth and sustainability in the hydrogen industry.

V – Hydrogen Hubs

The development cycle is a key motivator behind the U.S. Department of Energy's (DOE) Regional Clean Hydrogen Hubs Program, which aims to accelerate development of integrated hydrogen supply and demand ecosystems. A "focus on regional networks" is a core strategy to ramp up hydrogen industry scale in the DOE's Clean Hydrogen Roadmap.[48] As the DOE moves to deploy $8 billion in funds provided through the Infrastructure Investment and Jobs Act, it has earmarked $7 billion towards seven selected regional clean hydrogen hubs and is in the process of awarding each with funding.[49] The remaining $1 billion will be targeted at accelerating hydrogen demand. Texas' HyVelocity Gulf Coast Hydrogen Hub stands to receive $1.2 billion from the DOE as it develops large scale blue and green hydrogen production, hydrogen pipeline transportation infrastructure, salt cavern storage infrastructure, and demand development from refineries, petrochemicals, ammonia, e-methanol, and heavy truck mobility

[48] U.S. DOE, U.S. National Clean Hydrogen Strategy and Roadmap, pp. 28, 48-55.
[49] U.S. DOE Office of Clean Energy Demonstrations, Regional Clean Hydrogen Hubs.

applications.[50] A second Texas hub, the Horizons Clean H2 Hub, was designated as an alternate by the DOE, further demonstrating Texas' leadership position in the growing hydrogen economy.[51]

Texas leads in domestic and global markets in the race to establish this cycle of hydrogen industry development, but other regions throughout the United States and the world are also motivated by the economic opportunity. By understanding Texas' existing leadership position in the hydrogen industry, identifying the key enablers of and barriers to development, and prioritizing the appropriate industries on which to focus for development incentives, Texas can create a strategic plan to ensure it maximizes the economic opportunity for the state. Maintaining an early lead is critical for Texas to maximize its opportunity.

Part 4 – Texas is the Current Global Hydrogen Industry Leader

Texas' existing hydrogen industry is the most robust in the world, with leadership positions in hydrogen production, transportation, storage infrastructure and demand.

Finding 10: Texas is the current global leader in the hydrogen industry and can strengthen and further expand its leadership by supporting key enablers of hydrogen industry growth across the state.

I – Hydrogen Production in Texas Today

Texas currently produces 3.6 MTPA of hydrogen, one third of all the hydrogen produced in the U.S. Likewise, one third of all hydrogen production facilities in the U.S. are located in Texas,[52] with many more currently under development.[53,54,55] Beyond these "on-purpose" hydrogen facilities, Texas boasts significant additional hydrogen production as an intermediate product within refineries, petrochemical facilities and ammonia production units.[56] Notably, the three largest producers of hydrogen in the world (Air Products, Air Liquide, and Linde) each operate their largest respective hydrogen production networks in Texas.[57]

II – Hydrogen Transportation and Storage in Texas Today

Texas contains nearly twice the hydrogen pipeline mileage of all other states in the nation combined, with more than 1,000 miles of existing pipelines and multiple large scale hydrogen pipeline networks connecting major industrial centers from Freeport to Texas City to Houston to Port Arthur.[58] With respect to storage infrastructure, Texas contains the only three active salt cavern storage facilities for hydrogen in the U.S., in Moss Bluff, Clemens Dome and Spindle Top. These facilities represent a working

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[50] U.S. DOE Office of Clean Energy Demonstrations, Regional Clean Hydrogen Hubs Selections for Award Negotiations.

[51] U.S. DOE, https://www.energy.gov/articles/biden-harris-administration-announces-7-billion-americas-first-clean-hydrogen-hubs-driving; Horizons Clean Hydrogen Hub.

[52] The Center for Houston's Future, Greater Houston Partnership, Houston as the Epicenter of a Global Clean Hydrogen Hub, p.4.

[53] ExxonMobil, Low-carbon hydrogen: Fueling our Baytown facilities and our net-zero ambition.

[54] Linde, Linde to Invest $1.8 Billion to Supply Clean Hydrogen to OCI's World-Scale Blue Ammonia Project in the U.S. Gulf Coast.

[55] Chevron, Air Liquide, Chevron, LyondellBasell, and Uniper to Pursue Lower Carbon Hydrogen and Ammonia Project along the U.S. Gulf Coast.

[56] Baker Institute, Developing a Robust Hydrogen Market in Texas, p. 45.

[57] Air Products, Louisiana Clean Energy Complex, The World's Largest Hydrogen Pipeline System; Air Liquide, H2 Storage & Power; Linde, Linde Starts Up Major New Hydrogen Facility in the U.S. Gulf Coast.

[58] National Petroleum Council, Harnessing Hydrogen, Chapter 3: LCI Hydrogen – Connecting Infrastructure, p. 43.

capacity of 5.4 billion cubic feet and are already integrated into, or are in proximity to, existing pipeline networks.[59] Texas also boasts significant additional salt caverns where additional storage resources are planned and/or permitted (Big Hill[60] and Palangana[61]).

III – An Integrated Gulf-Coast Hub

While Texas is the clear leader among U.S. states in hydrogen production, transportation, storage and demand, its Gulf Coast neighbor, Louisiana, adds valuable synergies that can further enhance the region's potential as a global hydrogen epicenter. Louisiana holds a second position behind Texas in hydrogen production, pipeline infrastructure and demand. The presence of two existing interstate hydrogen pipelines connecting Texas and Louisiana make the Gulf Coast the first multi-state hydrogen hub in the U.S.

Building a robust infrastructure network between Texas and Louisiana offers numerous benefits. It de-couples demand from production, increasing optionality and improving the likelihood of new project development. Texas, with abundant renewable electricity supply, can produce and export electrolytic (renewable) hydrogen to Louisiana, creating a regional export market for facilities in Texas. An interstate hub with Louisiana also expands access to carbon storage pore space availability, salt cavern storage, reduced-emissions natural gas, renewable electricity and additional port access. This expanded resource pool enables large scale projects, critical for economies of scale, while enhancing resilience to risks such as hurricanes, freezes and power supply shortages that have affected both states in recent years.

The ability for Louisiana's hydrogen production to support Texas, and vice versa, through large scale, integrated infrastructure significantly mitigates key operational risks for Gulf Coast developers. This resilience is equally critical for supporting infrastructure, such as carbon dioxide transportation and storage networks, where blue hydrogen production in one state can rely on carbon management in the neighboring state. Development near the Texas-Louisiana border, in industrial centers such as Port Arthur, Beaumont, Orange, or Lake Charles, could also be greatly accelerated by a well-functioning interstate hydrogen ecosystem.

Part 5 – Critical Enablers of a Robust Hydrogen Ecosystem – Maintaining Texas' Leadership Position

The clean hydrogen economy is a complex, interconnected system of production, transportation and demand infrastructure, supported by energy and feedstock supply chains, all underpinned by foundational "soft" enablers. Identifying these critical enablers, along with Texas' strengths and weaknesses in each, provides a clear roadmap for Texas to maintain its leadership as the hydrogen industry evolves and expands.

I – Conventional Hydrogen Production

Conventional hydrogen production to date has been dominated by fossil fuel-based production pathways, such as "grey" hydrogen from steam-methane reformers of natural gas (SMRs), petrochemical and refinery off-gas purification, and gasification of natural gas, oil or coal. These existing

[59] Ibid, p. 47.
[60]Bulletin of the American Association of Petroleum Geologists, Big Hill Salt Dome, Matagorda County, Texas.
[61] Geological Society of America, Stratigraphy and Structure of the Palangana Salt Dome, Duval County Texas.

production methods demonstrate highly critical enablers foundational to all hydrogen production methods.

Recommendation 6: Texas should continue to support its efforts to ensure a low-cost, reliable supply of natural gas and electricity, which are foundational to all forms of hydrogen production and to the industries creating hydrogen demand.

Low-Cost, Reliable Natural Gas

Low-cost, reliable supply of natural gas feedstock represents one of the most important variables for conventional hydrogen facilities. Texas, as a global leader in natural gas production, offers a distinct advantage due to its abundant, low-cost natural gas supply. The state's existing natural gas pipeline infrastructure supports scalable development for new and existing facilities, ensuring that access to pipeline-supplied natural gas is available for project development in Texas' industrial clusters. Multiple pipeline networks in key industrial hubs provide a reliable supply that is resilient during potential disruptions and maintenance activities. The presence of multiple pipelines fosters a competitive market with low-cost transportation and energy rates. While Texas maintains positive momentum in maintaining low-cost supply, continued reliability and scalability of these critical networks should remain a focus.

Significant expansion in the hydrogen industry and other industries, such as liquified natural gas (LNG), can create increased natural gas demand in the future, potentially creating additional costs and developmental bottlenecks. Remaining ahead of the development curve and strategically over-sizing expansions of natural gas infrastructure will be vital to continued development of the hydrogen industry, particularly as low-cost, reliable, scalable natural gas supply remains foundational to blue hydrogen development (as discussed further below).

Additionally, the composition and purity of the natural gas supply will need to be thoughtfully considered moving forward as industry considers the risks and benefits of hydrogen blending into the existing natural gas system. Existing refineries, petrochemical facilities, LNG facilities and other process units, including hydrogen production facilities, have not been engineered to blend hydrogen into the natural gas feedstock and fuel supplies. Discipline in establishing the foundational science (studies, standards, etc.), diligence with evaluating system retrofits, and intentionality around where blending should occur (i.e., at the system level or at the site level) will all be critical as these strategies are evaluated and deployed. As the leader in natural gas production, existing industrial demand for natural gas, and the growing hydrogen industry, Texas should ensure safe, deliberate development with respect to hydrogen blending by embarking on foundational studies whose results can be used to set clear standards for blending into retrofitted systems.

Low-Cost, Reliable Electricity

Low-cost, reliable supply of electricity is also a key variable operating cost for conventional and renewable hydrogen. Like natural gas supply, reliability is paramount, and any upset (even for a matter of seconds) will create costly, extended facility downtime with potential impacts that cascade through the downstream supply chain. Texas is well-positioned as the leading state in the nation for electricity production (13 percent of all U.S. generation),[62] but recent years have demonstrated significant risk potential with respect to electricity price volatility and reliability (especially during high heat, freeze and

[62] U.S. EIA, Texas State Profile and Energy Estimates.

storm events). These risks are further amplified as significant increases in Texas electricity demand remain on the horizon. For example, Texas anticipates more electricity demand in the coming years as the state population continues to grow, data centers and green hydrogen production are deployed, and existing industries continue to electrify.[63] Even if new power production can be deployed fast enough to keep up with rapid demand growth, a focus on the location of the power production and demand is critical to avoid intrastate transmission between production and demand centers becoming a bottleneck. Deploying technology to de-bottleneck transmission (e.g., dynamic line rating) and accelerating permitting for both new transmission capacity and new power production interconnects will continue to be critical to support both existing and future hydrogen industry growth. Collaborations between the PUCT and ERCOT to further improve system reliability and ongoing efforts to improve winterization are both essential. As discussed further below, these critical efforts underpinning grid-scale reliability should be viewed as a complement to, and not a competitor of, renewable power generation development in Texas.

Hydrogen-Rich Off-gas Purification

Hydrogen-rich off-gas purification represents another well utilized conventional hydrogen production pathway and is an area of strength for Texas. The co-production of hydrogen-rich off-gas from olefins crackers, refineries and other petrochemical processes presents an efficient means of hydrogen production. With a significant portion of the nation's refineries, crackers and petrochemical facilities, Texas (and the broader Gulf Coast) dominates this type of hydrogen production and will continue to do so for the foreseeable future. As federal and international carbon intensity standards are developed, Texas should champion a consistent and equitable assessment of carbon intensity for co-product hydrogen that utilizes waste stream from these facilities as feedstock.

Texas' legacy of world scale, reliable, low-cost energy supply has enabled the hydrogen industry to blossom, but electric reliability threats and the potential for demand to outstrip existing energy infrastructure present real challenges that must be addressed to facilitate future industry growth in the state.

II – Blue Hydrogen Production (Fossil Fuel-Based with Carbon Capture and Storage)

As global demand for clean hydrogen grows, blue hydrogen, produced using fossil fuels and supplemented with carbon capture and storage, has immense potential as a scalable clean energy source. Blue hydrogen can be produced through several pathways, resulting in a range of carbon intensities depending on the extent of carbon capture applied to reduce facility emissions. For example, steam methane reformers (SMRs) can be built with or retrofitted with carbon capture technology, typically achieving a 50-60 percent capture rate. This has been demonstrated by Air Products' Port Arthur, Texas facility, where two world scale SMRs have been operating safely, reliably and economically for more than a decade, capturing nearly 1 million tons of carbon dioxide (CO_2) per year. For new facilities, Auto Thermal Reformers (ATR) and Gasifiers (most notably, partial oxidation gasification, or POX) represent established production technologies where carbon capture rates exceeding 95 percent are feasible, and therefore these are the primary focus for new blue hydrogen facility development.

Recommendation 7: To promote the growth of clean hydrogen production derived from natural gas (commonly known as "blue" hydrogen), Texas should prioritize the development of carbon dioxide

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[63] Baker Institute, [ERCOT and the Future of Electric Reliability in Texas. pp. 2-3](#).

management infrastructure, including pipelines and underground storage, as well as expand the supply of lower emission natural gas, such as Responsibly Sourced Gas (RSG) and Renewable Natural Gas (RNG).

Low-Cost, Reliable Natural Gas and Electricity

Like conventional hydrogen production, blue hydrogen production requires the same low-cost, reliable supply of natural gas and electricity as described above. In fact, with greater scale and capital intensity, blue hydrogen facility disruptions from power and gas outages can be even more impactful. ATR and POX facilities, which are fed with oxygen requiring substantial amounts of power, make low-cost electricity an increasingly critical component for blue hydrogen production. With low-carbon hydrogen derivatives (like ammonia) competing in global markets, Texas' global leadership in low-cost natural gas and electricity are a fundamental driver of the global competitiveness of Texas-produced blue hydrogen.

Low-Emission Supply of Natural Gas

The use of Responsibly Sourced Gas (RSG) as a feedstock has the ability to reduce the carbon intensity of blue hydrogen and its derivatives, generating economic value for the continued reduction of methane emissions in oil and gas production. Texas oil and gas industry leaders are already making meaningful progress in the RSG sector.[64,65] By continuing to support RSG by utilizing non-venting pneumatic controllers, methane leak monitoring and flare management, the state can create a significant demand for Texas-sourced natural gas used for blue hydrogen production, LNG exports and other emissions focused industries. This demand creates growth potential in the Texas natural gas industry, with up to 1 trillion cubic feet per year of new natural gas demand from Texas' blue hydrogen alone expected by 2050.[66] It also potentially positions Texas blue hydrogen as more cost effective and lower carbon than hydrogen produced in other geographies, making it more attractive as an export into global markets. Industry, academia, and other entities across Texas can take advantage of federal funding opportunities, such as the DOE's and EPA's $850 million funding opportunity[67] to reduce the cost of methane leak mitigation. To ensure an end-to-end value chain that maximizes economic value for Texas' gas industry, driven by downstream hydrogen demand, industry will need to align around consistent, certifiable RSG standards that align with policy incentive schemes. By maximizing the use of federal funding and championing consistent standards which incentivize industry demand, Texas can foster clean growth in its gas industry without requiring any new state incentives for methane emissions reduction.

Additionally, Renewable Natural Gas (RNG) development creates another significant potential for low emissions hydrogen production, with methane supplied from agriculture, municipal solid waste and other renewable sources. RNG is a 'drop-in-ready' low emissions option for existing hydrogen facilities, enabling carbon emission reduction without capital investment or project risk. Like RSG, clarity in RNG treatment across incentive schemes is a key enabler to understand the impact on overall hydrogen production emissions.

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[64] ExxonMobil, Driving reductions in Methane Emissions.

[65] Chevron, Methane Management: Keeping Methane in the Pipe.

[66] Assumes 21 MTPA per CHF Report, one third Blue per NPC report Exec summary p. 33. Blue H2 assumes approximately 1/3 NG volume per volume of H2 produced.

[67] U.S. EPA, EPA, DOE Announce $850 Million to Reduce Methane Pollution from the Oil and Gas Sector.

In both the RSG and RNG contexts, the natural gas industry generally operates on "book and claim" principles for most commercial transactions. A position allowing for book and claim will reduce market barriers and accelerate RSG and RNG production and utilization throughout the state.

Carbon Dioxide Management Infrastructure

Carbon dioxide management infrastructure is fundamental to blue hydrogen production, which requires robust and reliable carbon capture, utilization and storage (CCUS). CCUS infrastructure represents its own value chain, with new carbon capture facilities, pipelines for transport, and underground storage, which are all required to enable the low emissions footprint of blue hydrogen. Texas is already a leader in carbon capture and carbon dioxide (CO_2) transportation. The state has one of the nation's largest existing carbon capture projects in Port Arthur[68] and one of the nation's largest carbon dioxide pipeline networks, which today utilizes millions of tons of CO_2 each year in enhanced oil recovery operations (ExxonMobil / Denbury's Green pipeline).[69] The U.S. Gulf Coast has the largest storage capacity potential in the U.S.,[70,71] and Texas' well characterized geology, mature subsurface development industry and existing infrastructure make it well positioned to host the nation's premier carbon storage hubs. Several global energy operators (e.g., ExxonMobil/Denbury, Chevron, Oxy, Howard Energy Partners/TotalEnergies, BP, Repsol/Carbonvert) are developing scalable storage projects in Texas, including very large sections of the pore space under state owned submerged lands in the near offshore as secured through land lease offerings by the Texas General Land Office. Sustaining the proactive stance taken by the state to date to de-risk and accelerate CCS at scale in Texas will be critical to realizing the global potential of first mover hydrogen projects in the state.

Carbon dioxide network development will exhibit many of the same qualities of the hydrogen cycle of development discussed above for the hydrogen industry, with a focus on low-cost economics and reliability as CCUS enables reduced emissions across industries. Reliability of these carbon management networks will be essential since upset events could critically erode the tax credits and other value propositions of the low emissions industries served by CCUS infrastructure. Launching carbon "hubs" with at-scale demand for carbon capture, numerous storage wells and interconnecting pipeline infrastructure will be critical to achieving a cost profile to sustain accelerated industry development. While this development is foundational to blue hydrogen industry growth, it also provides an opportunity for independent market development in value chains where captured CO_2 becomes a revenue source for carbon management as a service.

Championing state support for the carbon management industry—including continuing to make state-owned pore space available for lease for carbon storage—and supporting efforts to educate Texans on underground storage will also be critical to ensure community support of development in the state. This community support has not been consistent in similar developments across the U.S., with notable resistance to projects in the Midwest.[72] As an industry with many similarities with upstream and downstream oil and gas production (requiring many of the same technologies and talent) and with the

[68] U.S. DOE Air Products hydrogen facilities.
[69] Denbury Company Presentation 2022.
[70] USGS, National Assessment of Geologic Carbon Dioxide Storage Resources - Results.
[71] National Petroleum Council, Harnessing Hydrogen, Chapter 1: Role of Low Carbon Intensity Hydrogen in the United States, p. 75.
[72] Sierra Club, Navigator Cancels CO2 Pipeline Project; Des Moines Register, On carbon pipelines, regular Iowans are winning some rounds against powerful ag interests.

potential to provide significant air quality benefits in Texas' industrial centers, a growing carbon management industry should be something welcomed by all Texans.

Although clean hydrogen and CCUS can develop independently from one another, blue hydrogen is fundamentally constrained in its growth by the capacity of the carbon management network. Even if all other elements are in place for a blue hydrogen project to flourish (demand, policy incentives, a supportive business environment, etc.), a blue hydrogen project will not proceed if CO_2 pipeline and storage capacity is not available, reliable and cost effective. It is therefore of paramount importance to Texas' clean hydrogen development that the CCUS industry be intentionally fostered parallel with clean hydrogen growth. Texas could also consider pathways that maximize future storage potential in the state, such as allowing for further research (and ultimately utilization of) composite confinement for storage as Texas develops its Class VI program at the state-level.

Finally, Texas should support efforts to secure federal funding for projects that support the development of Texas' carbon management infrastructure. The Bipartisan Infrastructure Law created up to $6.5 billion in funding which the DOE will deploy as these carbon hubs emerge.[73] Texas has already been selected for potential award connected to the DAC (direct air capture) hub funding with the South Texas DAC hub.[74] Similar efforts should be encouraged focusing on the CCUS funding and other grants that can kick-start Texas' CCUS development efforts.

Oxygen

Oxygen is another critical feedstock for blue hydrogen production. Many new blue hydrogen production facilities are designed using ATR and POX technologies with higher carbon capture potential and utilize oxygen as a feedstock. As a feedstock, oxygen requires the same high reliability already discussed for natural gas, power, and carbon management; even brief interruptions in supply will create costly facility disruptions. Oxygen produced at this scale and purity has traditionally been manufactured using Air Separation Units (ASUs), which utilize cryogenic distillation to separate oxygen from the air. While standalone ASU facilities are common throughout the world, robust oxygen pipeline networks that enable scalable, resilient supply are less common and will be yet another competitive advantage Texas holds as it secures a leadership position in the production of blue hydrogen. With several world scale oxygen pipeline supply networks already in place throughout the state, and significant announced growth on the horizon,[75] Texas represents one of the few oxygen hubs in the world, further reducing the cost and risk of developing blue hydrogen in the state. Beyond the reliability and cost effectiveness of the oxygen supply, the carbon intensity of the oxygen supply is yet again critical to the ultimate emissions footprint of the resulting hydrogen. As discussed further below, this creates further synergy between the production of clean hydrogen both produced as blue hydrogen (utilizing significant quantities of oxygen) and green hydrogen, which not only share hydrogen transportation and storage synergies, but also require significant quantities of reliable, low-cost, clean power. Texas' continued

[73] U.S. DOE, The Infrastructure Investment And Jobs Act: Opportunities to Accelerate Deployment in Fossil Energy and Carbon Management Activities.

[74] U.S. DOE Office of Clean Energy Demonstrations, Regional Direct Air Capture (DAC) Hubs Program – South Texas DAC Hub.

[75] Air Liquide, Decarbonization: Air Liquide selected to invest up to 850M USD in largest low-carbon oxygen production in the Americas.

support of oxygen facility and pipeline development will be an important supporting factor in the development of blue hydrogen in the state.

Carbon Capture Retrofits for Existing Hydrogen Facilities

In addition to being critical enablers for new construction of blue hydrogen facilities, the factors described above are also critical for the retrofit of existing, conventional hydrogen facilities with carbon capture. With the world's largest networks of existing hydrogen facilities, Texas has the greatest potential to utilize facility retrofits to jump start the clean hydrogen and CCUS industries within the state. Supported by 45Q tax credits at the federal level (discussed further below), these retrofits could provide some of the earliest, largest tranches of carbon dioxide to enable a scaled build out of carbon dioxide pipelines and corresponding storage. As discussed above, these retrofits have already been executed successfully at-scale in Texas, in the highest reliability context within one of the largest refineries in the U.S. Not only have these retrofits been executed successfully, but they have also been operated safely and reliably for more than a decade, demonstrating their immense potential as a part of the development of the clean hydrogen industry in Texas.

III – Green (Electrolytic) Hydrogen Production

Texas' clean hydrogen leadership potential also includes significant opportunity for green hydrogen production. Green hydrogen is produced most commonly by splitting water into hydrogen and oxygen molecules using renewable power in a process called electrolysis. Several electrolyzer technologies exist. Alkaline water electrolyzers are a well-established technology utilized by the chlorine industry for many years. Proton exchange membrane electrolyzers (PEM) have been recently utilized, demonstrating improved production pressure and rate flexibility. Finally, solid oxide electrolyzers (SOE) are currently in development with improved heat integration and energy efficiency potential.[76] All of these technologies are supported by the same foundational enablers: low carbon electricity, water and land availability and equipment supply chains.

Recommendation 8: To support the expansion of clean hydrogen production through electrolysis (commonly known as "green" hydrogen), Texas should adopt an "all of the above" energy approach, encouraging the expansion of low carbon electricity production from existing sources (wind and solar) and emerging ones (nuclear and geothermal).

Low Carbon Electricity

Electricity is at the heart of electrolytic (green) hydrogen production, representing 25 percent to 35 percent of the overall cost of green hydrogen.[77] The significant power consumed in electrolysis-based hydrogen production means that the carbon intensity of the hydrogen is a direct result of the carbon intensity of the electricity used. Thus, electrolytic production is nearly exclusively focused on clean electricity supply from solar, wind, hydroelectric, nuclear, geothermal, tidal and other low emission sources.

First, wind and solar have gained prominence as the lowest cost[78] scalable sources of low carbon electricity, leading overall power generation growth.[79] Renewable electricity generation potential varies

[76] National Petroleum Council, Harnessing Hydrogen, Chapter 2: Production At-Scale, pp. 22-31.
[77] Ibid, p. 59.
[78] Lazard, Levelized Cost of Energy Analysis – Version 16.0.
[79] U.S. EIA, Solar and wind to lead growth of U.S. power generation for the next two years.

by geography, with solar potential concentrated in the sunnier Western U.S. and wind in the Great Plains of the Midwest. These sources of electricity are also inherently dynamic and non-dispatchable, which may require overbuilding a renewable power resource to ensure maximum utilization at a given load. This dynamic production means that the right combination of both wind and solar can create significant cost reductions by optimizing the over-building requirements.[80]

Texas has a unique advantage with both solar and wind potential. Texas leads the nation in wind, with more than three times the capacity of any other state and produces nearly a third of all U.S. wind power production. Texas also generates the second most solar power in the U.S., approximately 13 percent of all U.S. solar power production.[81,82] These advantages are beneficial in the green hydrogen market, where the significant capital investment in electrolyzer equipment (also described as 'capacity factor') is critical for economic vitality.

Second, hydroelectric power has been utilized in the U.S. for more than a century as clean, dispatchable, baseload power. Unfortunately, the growth potential of hydroelectric power is limited, given its niche geographic requirements.

Third, nuclear fission has provided emissions free, baseload power supply for many years. This dispatchable power creates significant potential for clean hydrogen electrolysis, allowing for efficient use without overbuilding and maintaining very high-capacity factors. The potential for nuclear backed electrolysis is so great that it has earned the moniker "pink" hydrogen. Nuclear has historically been plagued by long development cycles, high regulatory scrutiny and significant capital requirements. However, small modular reactors and microreactors present an interesting opportunity for nuclear development to accelerate with smaller, replicable units. Some of these new designs are already progressing through regulatory approvals toward their first pilots.[83] With well-targeted regulatory and financial incentives, next generation nuclear has the potential to be a cornerstone of a multi-pronged solution to modernize and decarbonize the Texas electric grid, alleviating electricity generation and transmission constraints in the process and benefiting the production of green hydrogen.

Fourth, geothermal power represents another promising emissions-free, dispatchable power source. While near surface geothermal potential exists in rare geographic locations, enhanced geothermal systems, with deep wells exchanging heat within the earth, present a significant, scalable opportunity. Texas' geology and subsurface drilling workforce create clear advantages for the development of enhanced geothermal systems,[84] which can support green hydrogen production. Other emissions free power opportunities (e.g., tidal) are also in the early stages of development, and may, in the future, become a larger portion of the electricity slate.

Another additional benefit of green hydrogen's reliance on clean power is the potential to create new industrial supply chains and talent pools, which would be a natural complement to Texas' existing manufacturing expertise (e.g., specialty welders for nuclear reactors, drillers for geothermal wells, etc.).

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[80] National Petroleum Council, Harnessing Hydrogen, Chapter 2: Production At-Scale, pp. 58-61.
[81] Climate Central, A Decade of Growth in Solar and Wind Power: Trends Across the U.S.
[82] U.S. EIA, Texas State Profile and Energy Estimates.
[83] U.S. DOE, NRC Certifies First U.S. Small Modular Reactor Design.
[84] University of Texas, The Future of Geothermal in Texas: The Coming Century of Growth and Prosperity in the Lone Star State.

Beyond supporting Texas' energy needs, the human capital and manufacturing capabilities located in Texas could support nuclear and geothermal industry growth more broadly across the U.S., creating yet another inflow of value into the state and further establishing Texas as the energy center of the nation.

Efforts which bolster grid reliability, such as the Texas Energy Fund, should be sustained, and should be used to bolster both conventional generation as well as other dispatchable forms of energy, such as enhanced geothermal, next generation nuclear, and battery storage. Texas should consider incentives to enable new natural gas power producing facilities in proximity to hydrogen infrastructure to be "retrofit ready" for hydrogen co-firing in the future, which will further improve the resiliency of dispatchable power in the state (with stored hydrogen as a backup fuel), while ensuring new assets can serve multi-decade asset lifecycles far into the future. Texas should champion new development which minimizes impact to existing transmission bottlenecks, such as renewable electricity co-developed "behind the meter" with new green hydrogen production. Finally, as Texas works to maintain a strong pace of growth in new generation capacity (both clean and dispatchable), efforts should be made to improve the efficiency and consistency of the interconnection process, which can significantly delay new development.

Water and Land

In addition to clean power, the natural resources like water and land are critical for green hydrogen production. Electrolyzer produced hydrogen consumes 2.4 to 5 gallons of water per kilogram,[85] depending on the type of electrolyzer and ancillary systems like cooling towers. By 2050, Texas green hydrogen production could require as much as 92 to 173 million gallons of water per day[86]— equivalent to 0.7 percent to 1.4 percent of Texas' daily water consumption of 12.8 million gallons of water per day.[87] While not a significant use compared to irrigation, which uses 53 percent of state water, ideal locations for solar and wind power production, such as West Texas, face higher water stress.[88] Securing water resources locally may pose challenges. Ensuring alignment with municipal districts to prioritize water resource development and engagement with local communities is critical to align hydrogen projects with regional needs and avoid criticism.

Green hydrogen projects require significantly more land due to their reliance on renewable power, making their land footprint much larger compared to similarly sized fossil-based hydrogen facility. Facilities producing hydrogen from solar are estimated to require approximately 0.12 acres of land per kilogram of hydrogen produced.[89] Compared to conventional hydrogen production (0.0002 acres per kilogram of hydrogen produced),[90] these green hydrogen facilities may require as much as approximately 600 times the acreage of a conventional fossil-based hydrogen facility. As the largest state in the contiguous U.S., and with significant acreage of open land in West Texas co-located with optimal wind and solar resources, Texas has excellent land resources to enable green hydrogen production.

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[85] National Petroleum Council, Harnessing Hydrogen, Chapter 2: Production At-Scale, p. 71.
[86] Assumes 21 MTPA per CHF Report, one third Blue and two thirds Green per NPC report Exec summary, p. 33. Green H2 assumes approximately 2.4 to 4.5 kwh/kg per NPC report Chapter 2, p. 71.
[87] Texas Water Development Board, 2021 Texas Water Use Estimates Summary Report.
[88] Ibid.
[89] National Petroleum Council, Harnessing Hydrogen, Chapter 2: Production At-Scale, p. 73.
[90] Ibid.

Critical Equipment Supply-Chains

Green hydrogen production requires an extensive build out in the supply chain of critical equipment, much of which will require new manufacturing capacity. Electrolyzers and electrical equipment represent two noteworthy examples critical to green hydrogen electrolysis. Texas has an opportunity to incentivize these supply chains and manufacturing centers to develop within the state, which would create additional jobs, deepen Texas' industrial expertise in these new industries, and help to de-risk project development in the state. Recent announcements of a new electrolyzer gigafactory in Texas[91] highlight that these are real opportunities for the state. Federal funding is available to kick start the build out of this supply chain, and Texas should support efforts within the state in pursuit of these incentives.

IV – Alternate Methods of Hydrogen Production: Biogenic Green, Turquoise, White and Gold

Biogenic hydrogen provides an alternate path to green hydrogen distinct from the electrolytic production methods. The production of "biogenic green" hydrogen is similar to conventional or blue hydrogen production but uses biogenic hydrocarbons from a variety of original sources (e.g., used cooking oil, tallow, woody biomass, municipal solid waste, etc.) as a feedstock in the form of RNG, renewable propane, or other forms into a traditional hydrogen production facility. The production of biogenic green hydrogen can allow for low capital retrofits of existing facilities and creates very low or even negative carbon emissions when paired with CCUS. Texas has a significant U.S. retrofit potential for these types of facilities and has significant industry technical expertise given the leadership position in conventional refining and petrochemical production.

Examples of biogenic green hydrogen production include using RNG to feed conventional grey hydrogen facilities, the gasification of forest or agricultural waste, or integration of green hydrocarbon "off-gases" from renewable fuels (e.g., RD, SAF) facilities into hydrogen production. Using the low carbon feedstocks will significantly reduce hydrogen carbon intensity, further amplified if CCUS is used at the same facilities. Texas already has RNG and renewable fuels "off-gas" integration in place today. Many of these projects are challenged by feedstock supply chain logistics, so infrastructure supporting the build out of this renewable or circular hydrocarbon supply chains will continue to be essential to enable this part of the hydrogen industry to grow. Railroad, port and trucking infrastructure become more critical to these efforts, in addition to the foundational hydrogen elements discussed above and below (pipelines, CCUS infrastructure, low-cost reliable energy, etc.).

Methane pyrolysis (or "turquoise" hydrogen) provides another production pathway for low carbon hydrogen. In turquoise hydrogen production facilities, natural gas is converted into clean hydrogen and elemental carbon (e.g., "carbon black"). Like the conventional, blue, and biogenic green hydrogen processes, this pyrolysis represents a chemical process not unlike much of the existing Texas petrochemical industry, and, as such, these facilities could readily develop in Texas industrial centers. Critical enablers for these facilities include low-cost, reliable, low emissions-intensity natural gas (as discussed above for blue hydrogen), as well as a supply chain for the disposition of elemental carbon produced at the facility. Further work is likely needed to develop potential uses for this elemental carbon, which could someday be a commodity used as a raw material for manufacturing. While pyrolysis

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[91] John Cockerill, John Cockerill completes groundbreaking of the first US alkaline electrolyzer gigafactory in Houston.

will likely lag the scaled development of blue and green electrolytic hydrogen, the technology development will continue to be watched by industry as a potential for the future.

Finally, new production pathways are being evaluated for hydrogen in a subsurface context. Technologies are being developed to inject microbes into old oil and gas reservoirs which digest the remnant hydrocarbons and produce a hydrogen-rich off-gas (often described as "gold" hydrogen).[92] Likewise, there has been a recent increase in dialogue around the potential to prospect for existing supplies of hydrogen gas underground (often described as "white" hydrogen), similar to existing efforts to identify new oil and gas resources. Given the state's well-characterized geology and prowess in up-stream oil and gas exploration, Texas may be well positioned to lead this potential growth sector.

Each of these alternate methods of hydrogen production is in a fairly early stage of development and scale. Biogenic hydrogen is being produced at some scale today in Texas, methane pyrolysis is not yet demonstrated at-scale, and exploring for subsurface hydrogen is at a very early stage of development. Texas should continue to monitor these methods of hydrogen production and continue to encourage their development in the state. Each has potential to serve some proportion of the hydrogen value chain in the years ahead.

V – Hydrogen Transportation and Storage

Some of hydrogen's physical properties—an exceedingly low density and boiling point—make hydrogen transportation and storage both challenging and costly. Hydrogen is commonly transported via one of four methods:

- Transport as a gas in pipelines,
- Transport as a liquid in cryogenic tankers,
- Transport as a compressed gas, typically in tube trailers or high-pressure cylinders, and
- Transport via chemical carriers, typically for bulk export into global markets by converting hydrogen into ammonia, methanol or another hydrogen derivative and shipping in liquid tanks.

Hydrogen is commonly stored via one of four methods:

- Storage as a gas in subsurface formations, typically salt caverns,
- Storage as a liquid in cryogenic tanks,
- Storage as a compressed gas, and
- Storage as a chemical carrier, typically as ammonia, in liquid tanks.

Each of the hydrogen transportation and storage methods has its own benefits and drawbacks. States that establish and maintain leadership in hydrogen transportation and storage infrastructure will gain significant advantages in the growth of their hydrogen industries.

Recommendation 9: Texas should encourage significant expansion of infrastructure supporting the entire hydrogen value chain, including:

(1) input energy infrastructure (e.g., electricity transmission and natural gas pipeline de-bottlenecking),
(2) hydrogen production infrastructure and facilities,

[92] Cemvita, The Gold Standard for the Energy Transition.

(3) hydrogen transportation and storage infrastructure (e.g., hydrogen pipelines, underground storage and ammonia terminals),
(4) supporting infrastructure (e.g., carbon dioxide pipelines and underground storage), and
(5) demand infrastructure (e.g., hydrogen fueling networks and manufacturing facilities consuming hydrogen).

Wherever possible, this expansion should leverage existing infrastructure to minimize costs and environmental impact.

Hydrogen Transport via Pipeline

It is generally accepted that pipelines are the safest, lowest cost and most efficient manner to transport hydrogen in large quantities over long distances. Transport of hydrogen via pipeline can be measured in hundreds or thousands of tons per day,[93] whereas compressed hydrogen tube trailers carry only between one-half ton and one ton.[94] Advanced liquid or cryogenic hydrogen trailers (LH2) can carry more than four tons per load.[95] While that volume may be sufficient for hydrogen fueling stations, transportation of hydrogen for use in high-volume industrial loads will require pipelines, or, alternatively, large scale onsite hydrogen production adjoining the industrial plant operations. As described above in Part 3, the reliability and economies of scale enabled by pipeline networks create significant advantages over the standalone, onsite facility alternative.

Texas is the definitive leader with respect to its existing hydrogen pipeline networks, with more than 1,000 miles of hydrogen pipelines in service today.[96] However, hydrogen pipelines in Texas serve limited geographic markets and are insufficient for expanded markets beyond the concentration of refiners and petrochemical producers in East Texas and South Louisiana.

A dramatic expansion of hydrogen pipeline capacity is required for hydrogen to become a robust, low-carbon fuel option for the numerous end-use markets described above in Part 2. This same conclusion was made in the recent study on Hydrogen from the National Petroleum Council (NPC).[97] For Texas, expanded pipeline capacity will 1) allow Texas hydrogen production to access markets beyond the Gulf Coast region, and 2) allow renewable energy to be converted to hydrogen and hence better access high-volume domestic and export markets along the Gulf Coast. Hydrogen is also being considered by the DOE, electric utilities and renewable power developers as a possible solution for long duration, grid scale energy storage. If hydrogen proved to be technically and economically viable for this application, it could help support power grid stability at a lower cost than other alternatives currently available.

The implications of this discussion are:

- Hydrogen pipeline expansion is needed to increase market access for Texas-based hydrogen production. At least some of this expansion will need to focus on delivery to interstate markets.

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[93] 1 metric ton of hydrogen = 1000 kilograms(kg). 1 kg of hydrogen has approximately the same energy content as 1 gallon of gasoline.
[94] U.S. DOE, "Hydrogen Tube Trailers", https://www.energy.gov/eere/fuelcells/hydrogen-tube-trailers.
[95] Chart Industries, "LH2 Transport Trailer Specifications", https://files.chartindustries.com/LH2TransportTrailerSpecSheetST18600H.pdf; National Petroleum Council, Harnessing Hydrogen, Appendix D – Modeling Methodology, pg. 34.
[96] National Petroleum Council, Harnessing Hydrogen, Chapter 3: LCI Hydrogen – Connecting Infrastructure, p. 43.
[97] National Petroleum Council, Harnessing Hydrogen, Report Summary p. 58.

- Discussions on grid resiliency in Texas should be expanded to include hydrogen.

Additionally, as developers and policymakers consider expanding hydrogen pipeline infrastructure within the state, it will become increasingly important to distinguish between various types of hydrogen, which might be delivered in dedicated pipelines, each serving distinct purposes and requiring unique considerations.

"Pure" hydrogen pipelines serve industries requiring high purity "reagent grade" hydrogen used as a chemical feedstock; for example, refining, ammonia, renewable diesel, sustainable aviation fuel, e-fuels, direct-reduced-iron clean steel, and hydrogen for fuel cell or mobility applications. Most hydrogen pipelines in Texas today are pure hydrogen pipelines, and many operate at exceedingly high-quality specifications—some with less than ten parts-per-million of total impurities (99.999 percent hydrogen).

"Fuel Grade" hydrogen pipelines serve fuel switching purposes (e.g., furnaces, boilers, co-firing into gas turbines, etc.). While still predominantly hydrogen, these pipelines will contain significantly higher amounts of impurities: a 95 percent purity fuel grade stream of hydrogen contains 50,000 parts-per-million of total impurities, which is as much as 5,000 times that of pure hydrogen streams. At lower purity, these fuel-grade streams of hydrogen can be lower cost, which may be critical for fuel switching use cases, many of which have lower affordability limits relative to other hydrogen consuming markets.

"Blended" hydrogen pipelines primarily carry natural gas mixed with some hydrogen. Public discourse around these systems often focuses on retrofitting existing natural gas pipelines for partial hydrogen service. Since most natural gas pipelines were not originally designed for hydrogen service, retrofitting requires thorough due diligence, and further study is prudent to understand the limitations and requirements of these conversions.

Establishing common hydrogen gas quality standards for these pipeline systems will be critical to ensure multiple industries can use a shared network and meet downstream purification needs. The Compressed Gas Association (CGA) has published Commodity Specifications for Hydrogen (CGA G-5.3),[98] which may be useful to facilitate this common standard alignment across the industry.

Relatedly, policymakers globally have taken different stances on the "book and claim" method for hydrogen accounting. Requiring hydrogen to be transported in segregated piping to receive carbon intensity credits, as proposed in the latest draft of California's Low Carbon Fuel Standard (LCFS) rules for blue hydrogen, is sometimes described as impractical and may slow the adoption of clean hydrogen. A "mass balance" approach is often described as more practical, where clean and conventional hydrogen share common infrastructure with strict accounting to avoid double counting. The mass balance approach, akin to the book and claim approach used in natural gas markets, provides the most flexible accounting, where supply and demand can be maximally linked.

While hydrogen pipelines are capital intensive and require the appropriate economies of scale to cost effectively develop, they provide the safest and most cost-efficient transportation solution for large volumes of gas and are historically a common hydrogen delivery solution for large industrial customers throughout the state.

[98] CGA, Commodity Specification for Hydrogen.

Hydrogen Transport as a Cryogenic Liquid or Compressed Gas

When hydrogen is not transported as a continuous gas through a pipeline, it is often most economical to transport it as a cryogenic liquid, in its densest form. To liquefy hydrogen, it must be cooled below negative 423°F, an extremely low temperature just 36.5°F above absolute zero. As the second coldest fluid in the universe, liquid hydrogen requires highly specialized, vacuum insulated equipment for transport. The liquefaction process requires substantial power, and if clean hydrogen is needed this power may add to an already significant power requirement (e.g., for green hydrogen produced via electrolysis). If a low carbon intensity is desired, the additional power will need to be clean electricity, which can further increase costs. Despite these challenges, for smaller merchant quantities of hydrogen where a pipeline connection is practically or economically infeasible, delivery of liquid hydrogen via truck, rail or barge may be the lowest cost transportation option. The specialized nature of the storage equipment, along with the delivery mode limits (e.g., truck weight limits) constrains the size of liquid hydrogen deliveries to about 4 tons per load.

Hydrogen can also be delivered using similar modes of transport (truck, rail, barge, vessel, etc.) as a compressed gas. As with liquid hydrogen, the goal is to maximize the density of the hydrogen by compressing it to 2,000 to 3,600 psig. To contain gaseous hydrogen at these extreme pressures requires specialized vessels utilizing bundles of high-pressure tubes. While not as power intensive as liquefaction, compressing hydrogen to these high pressures does require significant power consumption. The pressure rating on these tubes often requires them to be incredibly thick, and as a bundle, the weight of the containers significantly limits how much hydrogen can be transported per load. Compressed tube trailers typically contain less than 0.5 tons per load, less than one-eighth ($1/8^{th}$) the hydrogen of a comparable liquid hydrogen load. Depending on the distance of transport, the added costs of additional mileage (for fuel), trucks and drivers often make this mode of transport less economical than for liquid hydrogen, except for small quantities of supply delivered short distances.

Texas currently has at-scale liquid hydrogen production today and several potential proposed projects which may significantly increase liquid hydrogen production capacity throughout the state. Continued support of liquid hydrogen development within the state is critical to ensure specific end markets within the state which consume hydrogen in smaller scale quantities continue to have access to lower cost hydrogen.

Hydrogen Transport via Chemical Carriers

Specialized storage equipment does not yet exist for overseas transport of liquid hydrogen at-scale because liquid hydrogen must be stored more than 160°F cooler than LNG. At least one demonstration of overseas liquid hydrogen transport has begun (Suiso Frontier),[99] but ships carrying liquid hydrogen have only one two-hundredth ($1/200^{th}$) the carrying-capacity of world scale LNG vessels. The inability to transport liquid hydrogen overseas has led to the transport of chemical carriers (also described as hydrogen derivatives) such as ammonia, methanol, e-methane and Liquid Organic Hydrogen Carriers (LOHCs), for overseas transport. Each of these chemical carriers requires the conversion of hydrogen into a new molecular form, adding cost and complexity.

[99] Baringa Partners, Hydrogen Council, Toward a New Era of Hydrogen Energy: Suiso Frontier Built by Japan's Kawasaki Heavy Industries.

Ammonia has an established global value chain in the fertilizer and chemical industry and has emerged as a promising chemical carrier for global hydrogen transport. By reacting hydrogen with nitrogen, energy can be efficiently transported as ammonia through existing supply chains, which can be stored and transported at a low pressure and -27°F, a much more manageable temperature than liquid hydrogen or LNG. In addition to its transport advantages, ammonia has other benefits which make it attractive as a chemical carrier of hydrogen. Ammonia is used in fertilizer manufacturing and as a feedstock for petrochemical processes, making it immediately useful without needing to convert it back to hydrogen. Ammonia is also being considered for additional end-uses, including as a bunker fuel for global shipping, which creates significant synergies (both on-vessel and at ports) for ammonia's uses as a global energy commodity. Ammonia does not emit carbon dioxide when used as a fuel and can be disassociated back into hydrogen at import terminals.

Many of these terminals are under development in Europe, where there is growing emphasis on balancing energy security with a desire to move to clean forms of energy. Additionally, ammonia produced using blue hydrogen benefits from the availability of at-scale nitrogen. As described above, blue hydrogen produced using POX or ATR technology often utilizes ASUs to produce oxygen as a feedstock. These ASUs split the air, making nitrogen as a natural co-product along with the produced oxygen. As oxygen production expands throughout the gulf coast alongside growing blue hydrogen production, nitrogen will be available at-scale and at low-cost along the same industrial corridors, readily enabling hydrogen conversion to ammonia for global export. This can be seen in action as many world scale ammonia production facilities develop in Texas and Louisiana. Texas' existing position as a large-scale ammonia producer and excellent access to port infrastructure (among the other numerous competitive advantages to produce reliable, clean, low-cost hydrogen described above) makes the state one of the most attractive locations in the global market for the production of clean ammonia.

Like ammonia, methanol is another existing globally traded chemical commodity that can be used as a chemical carrier for hydrogen. Hydrogen is converted to methanol using carbon dioxide or carbon monoxide. Like ammonia, methanol can also be utilized in existing petrochemical markets and is being considered as a bunker fuel alternative. While slightly easier to transport (at roughly ambient temperatures), methanol will emit carbon dioxide if used as a fuel, which complicates its uses as a clean energy alternative. Methanol can be created using carbon dioxide as a feedstock to mitigate the lifecycle emissions, but this adds significant feedstock costs to the economics of clean methanol production.

Other chemical carriers are also being considered, such as e-methane and LOHCs such as toluene. E-methane, like methanol, combines hydrogen with captured carbon dioxide to produce a drop-in natural gas (methane) alternative. Like methanol, the added feedstock costs challenge economics, but the ability to use the downstream natural gas infrastructure (including the global LNG supply chain) make e-methane an interesting opportunity where natural gas infrastructure will be hard to replace. LOHC's absorb hydrogen in a chemical reaction and can then be shipped as a liquid using conventional shipping technology. After transport overseas, the LOHC must be reprocessed to remove and repurify the hydrogen, and the LOHC without hydrogen is then shipped back to the original port.

Global policy shifts toward lower carbon energy in importing regions like Europe and Asia create significant opportunities for exports from regions with advantaged production economics for clean hydrogen derivatives. Texas can capitalize on this by producing clean ammonia, methanol, e-methane, and other derivatives at a low cost, supported by federal incentives, competitive natural gas and electricity prices and existing world class port infrastructure. As these international demand markets may be the first to grow due to international energy policies, Texas should focus on supporting the elements that facilitate these projects, including the production facilities for hydrogen, ammonia, methanol, and e-methane and the associated logistics and port infrastructure.

Subsurface Hydrogen Storage

Today, subsurface salt caverns are the preeminent means of storing hydrogen at-scale in large quantities. With 5.4 billion cubic feet[100] of volume of existing underground hydrogen storage, Texas leads both the U.S. and the world with existing salt cavern hydrogen storage. The geology that is most advantageous for hydrogen storage are the salt domes in the Gulf Coast region due to their high quality salt formation, which is capable of trapping hydrogen, a small molecule, in large volumes with minimal risk of leakage into the surrounding geology. The three active hydrogen storage sites in Texas are developed in three salt domes: Clemens, Moss Bluff, and Spindletop. Further expansion of underground storage for hydrogen will likely require the development of similar high-quality Gulf Coast salt domes and will be less likely in the lower quality bedded salt found in the West Texas region.

The only existing caverns that are capable of conversion to hydrogen caverns are natural gas storage caverns. This is due to the depth of the casing seat needed to gain high volume hydrogen storage. Most, if not all, existing caverns are utilized for natural gas storage to supply current power plants and customers, supporting the need for the development of salt caverns for hydrogen storage.

Salt cavern storage is complementary to green hydrogen production because hydrogen can be pulled from storage to support potential volatile green hydrogen production trends from renewable power. Salt cavern storage can also support seasonal demand patterns, such as hydrogen used for clean, dispatchable power. Integrated with pipeline networks, at-scale hydrogen storage also bolsters the reliability of the entire hydrogen supply chain, which is a critical enabler for future demand markets.

Geologists and other subsurface experts continue to research hydrogen storage in porous media, such as depleted subsurface gas reservoirs and saline aquifers. Significant research is still needed to assess the practicality and economic viability of hydrogen storage in other types of geological formations. Challenges include converting prior reservoirs not designed for hydrogen service and geochemical interactions that could create undesirable compounds, scale or precipitates. Despite these challenges, Texas should foster this research given the significant expanded hydrogen storage potential of porous media throughout the state, in the hopes that new storage locations are identified as the optimal salt dome locations become fully utilized. The Bureau of Economic Geology at the University of Texas may be a leading candidate to conduct this research.

Texas should continue to support hydrogen storage development in the state because it bolsters the reliability and resiliency of the hydrogen supply network and facilitates a flexible market in which production and demand do not need to be perfectly aligned at all times.

At-Surface Hydrogen Storage as Liquid Hydrogen, Compressed Hydrogen, or Chemical Carriers

Just as hydrogen can be transported through multiple modes in a liquefied form, a compressed form, or via chemical carriers, hydrogen can also be stored in these formats in tanks or vessels above the surface. As described above, each of these storage modes has drawbacks adding to the cost of storage: liquid

[100] National Petroleum Council, Harnessing Hydrogen, Chapter 3: LCI Hydrogen – Connecting Infrastructure, p. 41.

storage requires specialty tanks with vacuum insulation to handle cryogenic temperatures, compressed storage requires thick, heavy vessels built to withstand high pressure service, and chemical carriers require costly processing to convert hydrogen into other chemicals, such as ammonia or methanol.

Unlike subsurface storage, at-surface storage can be flexible for a given location. While salt dome formations exist in only certain geologic locations, tanks can be constructed at the surface in nearly any location where the land is available. While at-surface storage is more flexible, it is much more costly and is limited in scale relative to subsurface storage.

Like hydrogen transport, each storage method provides an optimum depending on the context, such as the total storage capacity and volatility of depositing hydrogen in and out of storage. Compressed gas storage provides limited scale, but lower power costs relative to liquefied storage, and may be more appropriate to balance moderate, high frequency supply and demand volatility in local contexts. Liquid hydrogen provides larger storage capacities, with the tradeoffs of more expensive equipment requirements (a liquefier facility vs. a compressor) as well as higher power consumption than compressed gas storage.

Both liquid hydrogen and compressed hydrogen offer transient storage options where hydrogen can readily be stored and converted back into usable hydrogen. Chemical carriers, on the other hand, provide significantly less flexibility, requiring large production facilities and costly re-conversion steps. Storage of chemical carriers such as ammonia or methanol may be appropriate in contexts where they are linked to the global supply chain (either at the export or import terminal), or in contexts where these chemicals can be directly utilized (e.g., in bunkering facilities where they are used as marine fuel alternatives). In all at-scale storage contexts, the hazards posed by the storage must be considered as the storage locations are finalized.

Like subsurface storage, at-surface storage facilities will be critical to the overall build out of the hydrogen industry, especially in development at the ports to serve demand to global markets. Texas should support storage development of hydrogen and hydrogen derivatives such as ammonia and methanol, recognizing that this storage infrastructure creates another advantage that will make Texas-sourced clean energy both the lowest cost and most reliable in the global market.

VI – Hydrogen Demand

As discussed in Part 2, growing demand for hydrogen will come from a myriad of new and existing end markets. For the hydrogen industry to grow to its full potential in Texas, the facilities and supply chains supporting these demand markets will also need to be enabled to thrive.

Hydrogen Export Demand

An estimated 10 MTPA of Texas' hydrogen is expected to support export demand in 2050,[101] as Texas serves global clean energy markets. As discussed above, hydrogen derivatives will primarily serve as chemical carriers for these exports. To meet this demand, Texas port infrastructure will be critical to support this export demand and should include berths for world scale loading of ammonia, methanol, synthetic methane and other chemical carriers, along with terminal tank capacity for storage. With international markets such as Europe and East Asia establishing policies that create hydrogen demand,

[101] The Center for Houston's Future, Greater Houston Partnership, Houston as the Epicenter of a Global Clean Hydrogen Hub, p.20.

Texas should prioritize the early expansion of export infrastructure across the state early in the transition.

Supply Chains and Infrastructure for Hydrogen Demand Industries

For many of the demand markets driving hydrogen growth in Texas, hydrogen is not the only critical feedstock. Often, the availability of other essential materials significantly influences the siting decisions for the production facilities. For example:

- Petrochemical production and oil refining require world scale supply of hydrocarbon feedstocks.
- Renewable fuels, such as renewable diesel and sustainable aviation fuel, require complex supply chains to feed biomass, used cooking oil, tallow and other renewable feeds to their facilities.
- Direct reduced iron (DRI) requires supply of heavy iron ore as a feed.
- E-fuels, synthetic methane and other “power-to-X” applications require supplies of carbon dioxide as a co-feed with hydrogen.
- Methanol production requires carbon monoxide.
- Ammonia production requires nitrogen.

Ongoing support for these supply chains and their infrastructure will be crucial to the development pace of each industry, ultimately tied to the demand for hydrogen. Including industrial heat applications (discussed below), industrial applications and feedstock are estimated to create a demand of approximately 6 MTPA of hydrogen by 2050.

Hydrogen Use for Power Production and Fuel Switching

Hydrogen use in power markets, gas blending or fuel switching often require retrofit activities to enable hydrogen utilization in existing infrastructure and equipment. Hydrogen blending into gas turbines and ammonia blending into coal fired power facilities often require aftermarket equipment modifications to accommodate the change. Burners may need to be replaced in fuel switching applications, and fuel piping may need to be replaced or thoroughly reviewed to ensure adequate volumetric flow and mechanical integrity of systems during hydrogen service. As discussed in Section 1, hydrogen blending into natural gas pipelines will also require thorough reviews, and possibly involve replacement of components for proper material of construction, changes in operational conditions, reductions of maximum operating pressures or changes of maintenance protocols. Texas should work with operators to ensure they are properly addressing hazards that arise with conversion of service. Many of these changes may require adjustments to air permits or other regulatory approvals. The TCEQ and other agencies should work to accommodate these modifications, recognizing that they will help Texas to produce cleaner energy and manufactured products while extending the lifespan of existing infrastructure.

Hydrogen is also being utilized for power or fueling using new equipment on which retrofitting is not required. To enable hydrogen demand from these applications, research, development and demonstration activities will be required to develop new equipment designs and ensure reliability in demonstration pilots. Once piloted, manufacturing will need to scale up to enable broad use of new fuel cells, boilers, furnaces, hydrogen turbines, hydrogen engines and other hydrogen-powered equipment.

Total demand for clean hydrogen in Texas for power generation, energy storage and natural gas blending is estimated to reach approximately 2 MTPA by 2050.[102]

Hydrogen Use for Mobility Applications

Heavy Duty Trucks

Total demand for clean hydrogen in the Texas heavy duty trucks sector is estimated to reach 2 MTPA by 2050.[103] Heavy duty trucks are an excellent application for hydrogen in Texas, as:

1) Heavy duty trucks represent approximately 5 percent of the vehicle population, but consume more than 20 percent of transportation fuel, making it a high impact market,
2) Many local fleets operate within a defined radius and return to base each night, reducing fueling infrastructure requirements, and
3) There are no other zero emissions options that meet the demand duty cycle for most heavy-duty trucks.

Texas already has several high concentration trucking markets, which would further reduce the cost of any new infrastructure.

Partly for these reasons, hydrogen for heavy duty trucks has been the focus of five active federal grants,[104] along with additional federal grant applications pending in Texas. The "Texas Triangle" is defined as the interstate corridor of I-10, I-45, and I-35 connecting Houston, Dallas/Ft. Worth and San Antonio. Three of four Texans live in this triangle and more than 10,000 heavy duty trucks traverse each leg of the corridor daily.[105] Intrastate freight is expected to double by 2050 from 2019 levels. This region is the planned location for at least five hydrogen fueling stations under the Texas Hydrogen and Electric Freight Infrastructure (Tx HEFTI) grant application, funded by the DOT's Charging and Fueling Infrastructure (CFI) Discretionary Grant Program. Additional public and private stations are being planned by industrial gas companies, truck stop operators, online consumer products fleet operators, ports and municipal transit agencies.

Hydrogen fuel cells offer improvements over batteries in electric vehicles—in weight and fueling time—making hydrogen better suited to heavy duty trucking and mining vehicles than batteries. Drayage trucks are usually Class 8 heavy duty diesel trucks, which are the single largest contributor to emissions of NOx among mobile sources along the Texas Gulf Coast.

Heavy duty truck traffic in the Texas Triangle

Through the Texas Hydrogen Infrastructure, Vehicle, and Equipment (THIVE) program, the TCEQ awarded $15 million in grants for the initial development of heavy-duty hydrogen trucks in Texas.[106]

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[102] Ibid, p. 23.
[103] Ibid, p. 23.
[104] U.S. DOE (H2LA) granted to GTI Energy consortium, U.S. DOT (Tx-HEFTI), granted to NCTCOG, U.S. DOT Federal Hwy Administration (CLEANSTACS) program granted to Port Houston, and DOT (I-45 Zero Emission Vehicle Plan), granted to NCTCOG, U.S. DOE (Gulf Coast Regional Clean Hydrogen Hub, known as HyVelocity), granted to HyVelocity Inc., October 2023.
[105] North Central Texas Council of Governments, Hydrogen in North Texas, p. 11.
[106] TCEQ, Texas Hydrogen, Infrastructure, Vehicle, and Equipment Grant (THIVE) Program Applications Selected for Funding Fiscal Year 2024.

Strong response to this initial grant program in Texas indicates a growing interest in hydrogen for heavy duty trucks.

Fuel Cell Passenger Vehicles

Fuel cell passenger vehicles have been demonstrated in the U.S. (primarily in California) since the late 1990s. However, only Toyota, Honda and Hyundai have launched hydrogen vehicles commercially. While conventional wisdom suggests the zero-emission passenger vehicle market will be dominated by battery-electric vehicles, fuel cell vehicles offer some advantages. Hydrogen fueled vehicles have a zero emissions capability but can be refueled as quickly as gasoline vehicles and provide a longer range, using public fueling stations. If hydrogen fueling stations become more available (for example, to supply heavy duty trucks), hydrogen-fueled passenger vehicles could become more popular in the state.

Hydrogen for Marine Applications

The maritime industry contributes between 2-3 percent of global greenhouse gas emissions. Both ammonia and methanol are being considered by shipbuilders as low emission fuel alternatives for global shipping.[107] In late 2023, shipping giant Maersk signed long term offtake agreements for annual volumes of 300KT, starting in 2026, to fuel its first 12 methanol-enabled vessels. This transition in the world vessel fleet will necessitate the availability of fueling capabilities at ports of call on the Gulf Coast,[108] creating an ancillary market for clean hydrogen. These marine applications are estimated to reach a demand of approximately 0.4 MTPA in 2050.[109]

Hydrogen for Aviation

Total hydrogen demand for use in aviation is estimated to reach approximately 1.1 MTPA by 2050.[110] This demand will shift from supporting conventional refining to hydrotreating sustainable aviation fuel (SAF), producing e-fuels like e-SAF (synthetic jet fuel from clean hydrogen and carbon dioxide), and eventually using hydrogen directly as a fuel. With very few viable alternatives to these hydrogen enabled fuels, it is very likely that as the aviation industry continues to grow and moves towards lower emission fuels that it will drive hydrogen demand. With existing world scale production of renewable fuels in Texas, it is very likely that Texas will be a major contributor to the SAF market. Likewise, with world leading co-located hydrogen and carbon dioxide infrastructure, Texas is likely to be a world leader in the production of e-fuels such as e-SAF.

VII – Foundational Soft Enablers

In addition to the physical infrastructure required to enable the development of the hydrogen industry, there are “soft” enablers which are just as critical to the build out of the industry: workforce, talent and project execution capability; technology, research, development and demonstration; carbon intensity measurement, verification and certification; and financing and insurance. As discussed in Section 1, a consistent and efficient permitting and regulatory environment is yet another critical soft enabler.

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[107] Argus Media, Methanol vs. Green Ammonia: The future of marine fuels.

[108] Orsted, Orsted and Maersk sign landmark green fuels agreement, as Orsted enters the U.S. Power-to-X market.

[109] The Center for Houston’s Future, Greater Houston Partnership, Houston as the Epicenter of a Global Clean Hydrogen Hub, p.21.

[110] Ibid, p. 24.

Workforce, Talent and Project Execution Capability

One of the most critical enablers of hydrogen industry development in Texas is a workforce which can develop, design, construct, operate and maintain the world scale facilities and infrastructure of the growing hydrogen industry. This workforce needs to have both the capacity and the talent to support the significant development that will drive the hydrogen industry's growth.

With respect to workforce capacity, Texas' state population is among the fastest growing in the country. Between 2021 and 2022, the Texas population added nearly half a million people—more than any other state—and led the nation in job growth in 2022, adding 650,100 new nonfarm payroll jobs.[111] This growth is anticipated to continue, driven by a favorable jobs outlook, business friendly state policy, and no personal state income tax. A recent McKinsey study estimates that a clean hydrogen economy in Texas could potentially create more than 180,000 new and repurposed jobs by 2050[112] and generate $100 billion in state GDP, representing around 6 percent of state GDP.[113] These jobs and economic growth will continue to attract new talent to Texas, which will enable the workforce to scale to a size where it can support the growing industry.

As important as the size of the workforce, is its talent. The expertise required for the hydrogen industry is multi-dimensional, and each role is critical to the build out of the industry throughout the state. Texas contains many of the world's preeminent engineering, procurement and construction firms, which have a long history of world scale project development in Texas supporting the existing energy, petrochemical, power and other industries throughout the region. The construction and maintenance of these facilities require large numbers of welders, scaffolders, pipefitters, millwrights, technicians, crane operators, boilermakers and numerous other supporting trades and crafts. Research and development activities supporting technology improvement will require engineers and technologists. Underground carbon and hydrogen storage development will require the unique skills of the upstream oil and gas industry with exploration, drilling, completion and operation of many new carbon storage wells and hydrogen salt caverns throughout the state. The transportation of hydrogen and its derivatives to market will require the talent of the midstream oil and gas industry, with expertise in construction, operation and maintenance of pipelines. Transport by other means will require drivers, dockworkers and others supporting hydrogen transport via rail, road or vessel. Given Texas' leading role in today's hydrogen economy, a significant amount of hydrogen specific expertise is also present in the region, with engineers, operators, pipeline technicians and many of the trades outlined above supporting hydrogen production and transportation for decades.

Supported by this workforce, Texas has the talent required to succeed in world scale project execution, and this capability has been demonstrated numerous times in the region on large, complex projects supporting the energy and petrochemical industries (e.g., LNG export terminals, ethylene crackers, refineries, etc.). In addition to talent, Texas contains other critical elements supporting world scale project execution, including construction equipment (e.g., cranes, pile drivers, etc.), port facilities and thoroughfares (to deliver large equipment and modules to site) and manufacturing capabilities.

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[111] Texas Tribune, Texas led country in new jobs in 2022 as state's unemployment rate fell below 4%.

[112] The Center for Houston's Future, Greater Houston Partnership, Houston as the Epicenter of a Global Clean Hydrogen Hub, p. 45.

[113] Ibid. p. 29.

Texas holds a significant advantage in the hydrogen industry due to its large, growing workforce, diverse talent pool, hydrogen-specific technical expertise, and world scale project execution capabilities. Texas should work to maintain this advantage by promoting workforce development efforts between communities, universities and companies to ensure each trade and skill set has a robust pipeline of talent. These efforts will not only enable the success of the hydrogen industry but will also maximize the economic benefits to the many Texans gainfully employed in excellent careers created by the growth of the hydrogen industry within the state.

Technology, Research, Development, and Demonstration

To continue reducing the cost of hydrogen production, technology improvement will be required to develop more efficient, reliable, and lower carbon-intensity methods for production, transportation and storage of hydrogen. Beyond having the talent required to drive these activities in Texas (described above), these technological improvements are accelerated by collaboration between corporations, research institutes, universities, incubators (e.g., Greentown Labs)[114] and other stakeholders. Gaining insights from existing hydrogen production equipment in operation today is a helpful input into the research and development process, and de-risks demonstrations and pilots essential for scaling new technologies. Technology advancements will span the hydrogen value chain, including production equipment (e.g., electrolyzers), end-use applications (e.g., fuel cell vehicles, hydrogen burners, etc.), storage (e.g., subsurface storage in porous media) and dispatchable clean power production (e.g., small modular nuclear reactors, enhanced geothermal, etc.). Supporting this technology development in Texas will boost hydrogen industry and drive economic growth in Texas' labs, universities and manufacturing facilities.

Carbon Intensity Measurement, Verification and Certification

As described in Part 3, the carbon intensity of hydrogen supply will become a focus as the hydrogen industry develops in the coming years. Aligning around common carbon intensity measurement methods will reduce complexity and ensure production within the state meets requirements in the broadest range of demand markets. In addition to the calculation method and input assumptions, other policy constraints and requirements can also have a significant impact on perceived carbon intensity. Practical policies allowing for "book and claim" or "mass balance" to allow for commingling of clean and conventional hydrogen within existing infrastructure should be championed to enable the broadest uptake in clean hydrogen demand across markets. Creating consistent, trustworthy verification and certification methods will also be critical to assure off-takers and other stakeholders that the carbon intensity is being calculated and reported with integrity.

Financing and Insurance

The many large scale infrastructure development activities that will be a part of the growing hydrogen industry within the state will require financial support and services in the form of financing and insurance. To encourage large inflows of private capital and minimize the financial burden to the Texas taxpayer associated with industry development, a robust competitive market with a level playing field must be maintained. This will ensure that capital flows from project financing, corporate equity, bond issuance and other avenues can secure the required returns on investment to fund numerous world scale developments within Texas, from new hydrogen facilities and pipelines to new facilities that utilize hydrogen and port infrastructure for global export. To manage the risk associated with these complex,

[114] Greentown Labs, Greentown Houston.

capital-intensive endeavors, robust insurance instruments must exist. Many such instruments are being used today to support ongoing world scale development in the region, but there are new areas associated with hydrogen industry development (e.g., insuring risk associated with long term carbon storage) which may need further refinement.

VIII – Policy and Incentives

The transition to cleaner energy sources and production methods requires substantial investment in facilities and infrastructure, presenting both costs and opportunities. To incentivize private investment, governments both domestically and internationally are evaluating and implementing policies and incentive frameworks that will create significant motivation to spur the rapid development of the global hydrogen industry. Texas' state level policies should be informed by an awareness of U.S. and international policies and should be crafted to complement these policies with strategic support to maximize the benefits to Texas citizens while minimizing the cost to Texas taxpayers.

U.S. Federal Policies and Incentives Accelerating Hydrogen Supply

The U.S. Department of Energy has been the primary federal governmental agency responsible for the development of "clean" hydrogen technology via its funding programs and decades long departmental advocacy for hydrogen as an important component of a national clean energy portfolio. While hydrogen programs have been funded in both Democratic and Republican administrations, funding for hydrogen has increased dramatically during the Biden administration (along with funding for other low carbon energy solutions). In June 2023, the National Hydrogen Roadmap[115] was released by the Department of Energy. This document outlines three key strategies that could have a significant impact on the Texas hydrogen industry. Those three strategies are:

- Target strategic high-impact end-uses
- Reduce the cost of hydrogen
- Regional networks/hubs

Target Strategic High-Impact End-Uses

It is notable that at least six of the seven high-impact end-use hydrogen applications identified by the DOE in its National Hydrogen Roadmap are significant markets for Texas. As outlined in a recent study by the Center for Houston's Future and the Greater Houston Partnership[116] on hydrogen in the Texas Gulf Coast region, mobility, process heat, chemical feedstocks, ammonia and power generation will account for much of the region's anticipated 21 MTPA of clean hydrogen end-use by the year 2050. Current use in Texas is approximately 3.6 MTPA. Current and anticipated Texas demand aligns well with the DOE's targeted end-use applications leading to increased interest and investment in Texas by federal agencies in the form of research and development grants, technology demonstrations and (potential) direct incentives.

Reduce the Cost of Hydrogen

The second DOE clean hydrogen strategy is to reduce the cost of hydrogen. Again, Texas figures prominently to enable this goal to be achieved. Existing energy production and infrastructure can be

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[115] U.S. DOE, U.S. National Clean Hydrogen Strategy and Roadmap.

[116] The Center for Houston's Future, Greater Houston Partnership, Houston as the Epicenter of a Global Clean Hydrogen Hub.

leveraged, and in some cases repurposed, to generate clean, low carbon hydrogen. DOE plans to achieve lower hydrogen costs with a combination of:

- Investment in research and development to improve technical efficiencies, reliability and lower equipment costs,
- Investment in hydrogen infrastructure build out initiatives ranging from training for permitting officials to loan guarantees for clean energy capital investments, and
- Direct incentives such as 45V, 45Q, and 48C [117].

According to the Baker Institute, factors that will support Texas' continued hydrogen "low-cost leadership" include but are not limited to:[118]

- "A robust industrial sector, especially in petroleum products, chemicals, plastics, and rubber manufacturing (13.2 percent of U.S. GDP in these sectors, collectively, in 2021) co-located with the nation's leading energy ports (Corpus Christi and Houston).
- An existing hydrogen market with two-thirds of U.S. hydrogen transport infrastructure.
- An investment environment that is generally supportive of infrastructure development.
- A large natural gas production, transport, storage, and end-use footprint (accounting for 60.5 percent of U.S. GDP in oil and gas extraction and 24.6 percent of U.S. GDP in pipeline transportation in 2021).
- Vast, accessible and economical natural gas supply.
- Excellent geology for permanent underground storage of carbon dioxide, enabling the production of low-carbon hydrogen at scale from natural gas feedstock (i.e., "blue" hydrogen).
- Deep expertise in logistics and supply chain management (accounting for 11.6 percent of U.S. GDP in wholesale trade and 10.0 percent of U.S. GDP in transportation and warehousing)."

Additional factors include extensive wind and solar resources for the production of "green" hydrogen and significant salt dome resources to support tremendous subterranean hydrogen storage capacity. These factors could position Texas to be a global low-cost hydrogen leader as early as 2030 for hydrogen from both gas feedstocks and electrolytic production pathways.

Texas production costs in 2030 could be globally competitive for both electrolysis and natural gas sourced hydrogen.[119]

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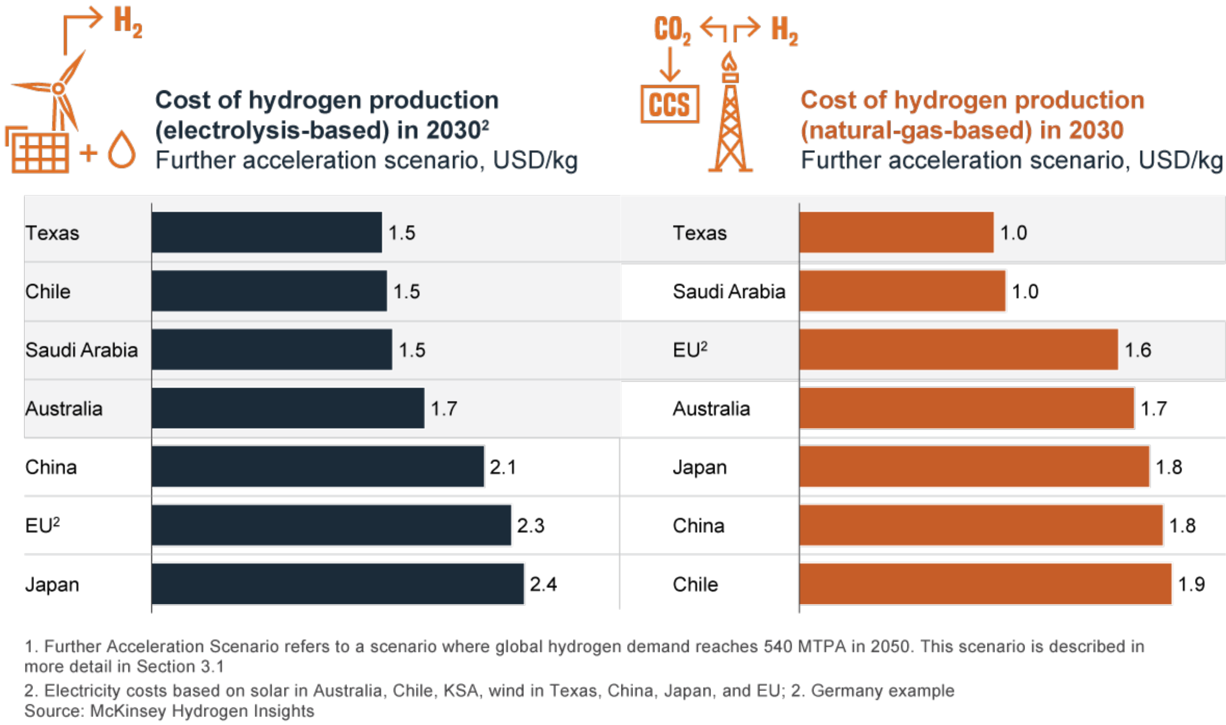
[117] Note that these incentive programs are administered by the Treasury Department rather than DOE. However, DOE had input in drafting final rules on program implementation. Federal Register, Section 45V Credit for Production of Clean Hydrogen.
[118] Baker Institute, Developing a Robust Hydrogen Market in Texas, p. 5.
[119] The Center for Houston's Future, Greater Houston Partnership, Houston as the Epicenter of a Global Clean Hydrogen Hub, p. 16.

Figure 1: Anticipated Cost of Hydrogen Production in 2030



Source: The Center for Houston's Future, Greater Houston Partnership, Houston as the Epicenter of a Global Clean Hydrogen Hub, p. 16.

Regional Networks/Hubs

On November 20, 2024, the DOE announced that the Gulf Coast Regional Clean Hydrogen Hub (known as "HyVelocity") completed negotiations and was awarded a federal grant up to $1.2 billion in order to establish a regional hydrogen hub, with $22 million for phase 1 of the project plan. This completed an application process that began almost three years prior to the announcement, with a Texas and Southwest Louisiana consortium administered by GTI Energy, with founding partners Center for Houston's Future, the University of Texas at Austin, HARC and Port Houston being selected as one of seven regional teams from 80 initial applicants.[120]

The third DOE strategy is the establishment of regional networks or hubs for early production and use of clean hydrogen. DOE's Hub funding opportunity states:

> *"The H2Hubs will form the foundation of a national clean hydrogen network that will contribute substantially to decarbonizing multiple sectors of the economy. Matching the scale-up of clean hydrogen production to a growing regional demand is a key pathway to achieving large-scale, commercially viable hydrogen ecosystems. H2Hubs will enable this pathway by demonstrating low-carbon intensity and economically viable hydrogen-based energy ecosystems that can replace existing carbon-intensive processes. This will accelerate the deployment of these technologies and enabling*

[120] HyVelocity Hub, HyVelocity Hub: Rapidly Scaling Clean Hydrogen Supply and Demand.

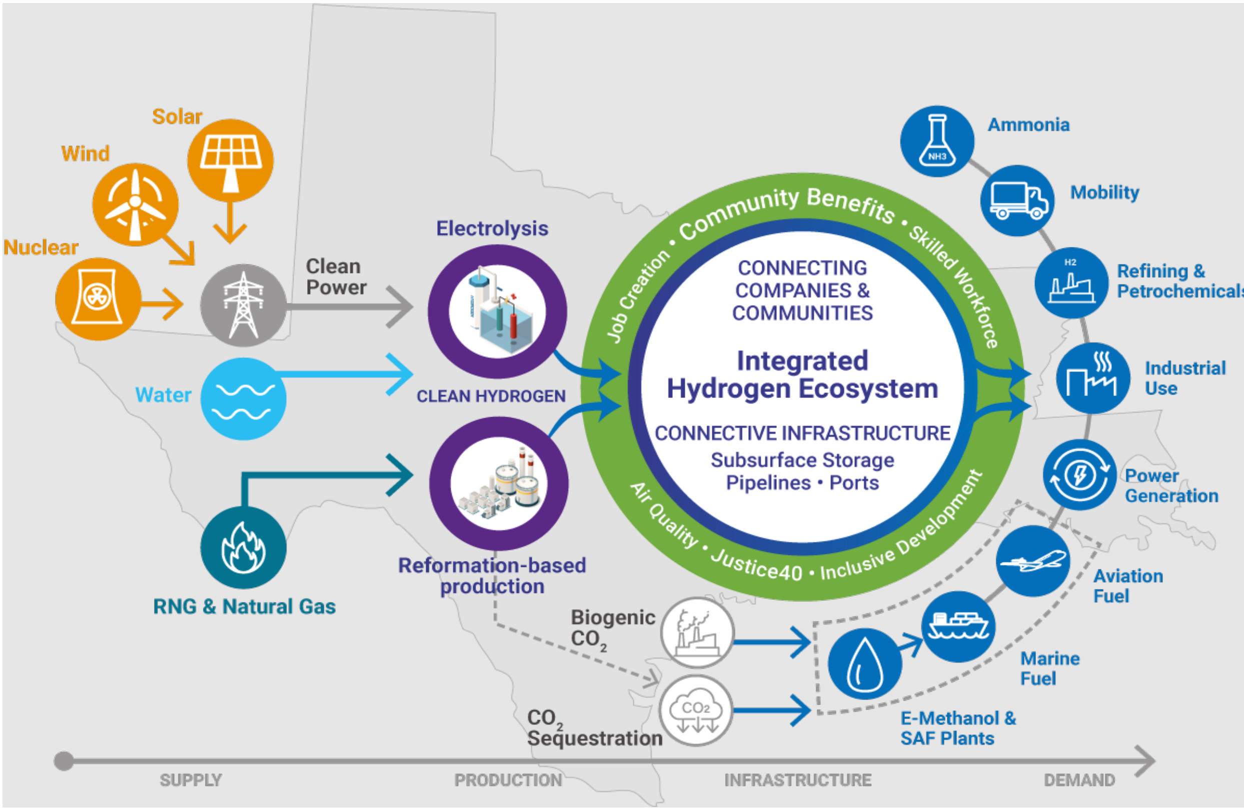
infrastructure, attract greater investments from the private sector, and promote substantial U.S. manufacturing of numerous hydrogen related technologies."[121]

Today, the hydrogen assets along the Texas Gulf Coast are, by definition, an "H2Hub" containing the world's largest concentration of hydrogen producers, refining and petrochemical consumers and connective infrastructure all in close proximity. The assets are ready-made for conversion into a clean H2Hub. The Gulf Coast hydrogen complex, stretching from Corpus Christi, Texas to New Orleans, Louisiana produces 3.5 million metric tons per annum (MMTPA), which is 1/3 of annual U.S. hydrogen production, through a system of 48 production plants and more than 1,000 miles of dedicated H2 pipelines.[122] This is more than one-half of the nation's current capacity pipelines. Subsurface geology that is well suited for carbon capture and storage (CCS) and for commercial scale salt cavern hydrogen storage is co-located within this footprint. In addition, the ERCOT power market overlays the hydrogen hub's footprint. The ERCOT market leads the nation in renewable energy deployment (more than 36 gigawatts of wind, the largest portfolio in the country, and more than 14 gigawatts of utility scale solar) which supports both grid and direct-connected green hydrogen projects.

The HyVelocity hub represents a clean hydrogen investment of approximately five or more private dollars for each federal dollar invested. As shown in the figure below, proposed infrastructure includes clean ammonia production for export to markets in Europe and Asia, e-methanol as a bunkering fuel for marine shipping, open access hydrogen pipelines, hydrogen storage, hydrogen production (both from electrolysis and from natural gas with carbon capture and storage), hydrogen fueling stations for on-road vehicles, and hydrogen liquefaction.

[121] U.S. DOE, Funding Opportunity Announcement (FOA) Number: DE-FOA-0002779, p. 6.
[122] HyVelocity Hub, HyVelocity H2 Hub Frequently Asked Questions.

Figure 2: Gulf Coast Clean Hydrogen Hub (HyVelocity Hub) Value Chain from Energy Source to End-Use



Source: HyVelocity Hub.

The threshold for carbon intensity for the HyVelocity hub is a relatively low carbon intensity score of 2 kg CO_2e/kg H_2 or lower. This is lower than the carbon intensity score of 4 kg CO_2e/kg H_2 required by the Inflation Reduction Act containing the 45V incentives.[123]

The Inflation Reduction Act and Hydrogen Production

The Inflation Reduction Act (IRA), signed into law in August 2022, created and augmented several tax credit provisions which serve to reduce the cost of hydrogen production in the United States.

For clean hydrogen produced using fossil fuels with carbon capture (blue hydrogen), the existing 45Q tax credit was extended and enhanced, providing an $85 tax credit per metric ton of carbon dioxide captured over a twelve-year period. A $60 tax credit per metric ton is also available for carbon dioxide capture for utilization into Enhanced Oil Recovery (EOR) or other use cases. As discussed above, with carbon dioxide transportation and storage infrastructure development critical to the expansion of blue hydrogen production, the 45Q tax credit expansion creates significant momentum for the development of the carbon management industry.

The most noteworthy provision in the IRA related to hydrogen production is the creation of a new 45V hydrogen production tax credit, with tiered credits (from $0.60 to $3.00) per kg of clean hydrogen produced, paid over a ten-year period. While the detailed rules supporting the 45V are still under review

[123] DOE embraced "carbon intensity" as a more objective alternative to "colors" of hydrogen. See Appendix I on hydrogen colors.

by the Internal Revenue Service in collaboration with the DOE, the 45V credit, in conjunction with the 45Q credit provide the strongest policy support for green and blue hydrogen production in the world, creating significant motivation for any company considering hydrogen production to locate their production facilities in the U.S. With Texas as the preeminent location in the U.S. for existing hydrogen production, infrastructure and demand centers, these tax credits create significant attention on developing hydrogen production in Texas from private investors all around the world.

Beyond the 45V and 45Q tax credits, the IRA provided further indirect support to hydrogen through other provisions. The renewable energy production tax credit modified and extended the credit supporting renewable electricity, which provides up to 2.75 cents per kWh produced. With green hydrogen critically enabled by clean electricity production, this credit creates further support for green hydrogen in Texas, where renewable electricity is experiencing the highest growth rates in the U.S. The IRA also introduced a tax credit for sustainable aviation fuel (SAF) for $1.25 per gallon. As described above, with SAF requiring large quantities of hydrogen for hydrotreating, this credit will indirectly increase demand on hydrogen. With large SAF projects already in progress in Texas, this credit will directly increase Texas hydrogen demand.

Other Federal Grants for Hydrogen and Hydrogen-Related Infrastructure in Texas

While the HyVelocity hub is the largest and most well-known DOE investment in Texas clean hydrogen, there are other, equally important federal programs focused on deploying hydrogen infrastructure in Texas. Other federal grants related to hydrogen could facilitate commercial launch of businesses focused on clean hydrogen as well as accelerating interregional regulatory, technical and commercial networks.

Table 1: Other federal hydrogen grants throughout Texas

Recipient	Status	Agency	Amount	Description
Port Houston	Awarded	FHA (DOT)	$27MM	Purchase of zero emission drayage trucks
NCTCOG	Complete	DOT	$75k	Planning I-45 fueling corridor
NCTCOG	Awarded	DOT	$70MM	Constructing 5 fueling stations in Texas Triangle
GTI Energy	Awarded	DOT	$1.5MM	Houston to LA (H2LA) fueling infrastructure planning
Port Houston	Applied	EPA	$100+MM	Purchase of Heavy Duty H2 Fueled Trucks and H2 fueling infrastructure
HyVelocity Inc.	Awarded – in negotiations	DOE/OCED	$1.2B	Establish Gulf Coast Regional Clean Hydrogen Hub
Frontier Energy, University of Texas, and GTI Energy	Awarded	DOE	$13MM	H2@Scale demonstration facility

Source: U.S. DOT Federal Highway Administration, Biden-Harris Administration Announces Nearly $150 Million in Grants to Help Reduce Truck Air Pollution Near America's Ports; Texas Standard, Federal grant will bring hydrogen truck fueling to Texas; U.S. DOE, Biden-Harris Administration Announces Funding for Zero-Emission Medium- and Heavy-Duty Vehicle Corridors, Expansion of EV Charging in Underserved Communities; U.S. DOE Office of Clean Energy Demonstrations, Regional Clean Hydrogen Hub Selections for Award Negotiations; The University of Texas at Austin Cockrell School of Engineering, First-of-its-Kind Hydrogen Proto-Hub Galvanizes Production of Low-Carbon Hydrogen.

Policy Discussion on Hydrogen Pipelines

Texas has established an early lead in the development of the hydrogen industry, in large part due to its leadership position with respect to hydrogen pipeline infrastructure. However, it is widely recognized that a significant scale-up of hydrogen pipeline infrastructure will be necessary for Texas' hydrogen industry to reach its full potential as the global center of hydrogen production. Enabling the development of hydrogen pipelines (in addition to other critical supporting infrastructure, as described above) should be a priority for Texas as it works to accelerate the hydrogen industry within the state.

Texas' existing pipeline regulatory framework has created an environment which fosters pipeline infrastructure development, with the state containing 1/6th of all pipeline mileage in the U.S., more than any other state in the nation.[124] The current pipeline regulatory approach has led to successful development of both the largest network of intrastate natural gas pipelines (representing half the intrastate pipeline mileage in the nation[125]) and the largest hydrogen pipeline networks in the world. Maintaining this successful pipeline regulatory framework, which accommodates investment from developers of both private and common carrier[126] hydrogen pipelines, will be critical to enabling the significant build-out of infrastructure required to support the exponential growth of the hydrogen industry within the state.

In addition to intrastate pipeline development within Texas, infrastructure development will also be critical to connect Texas to external demand markets. Significant build-out of new interstate pipelines will be a critical part of this development, especially in the later phases of hydrogen industry growth, as mature hydrogen production hubs become linked via interstate pipelines to distant demand hubs. Likewise, as discussed above, significant growth will be required in port infrastructure supporting global exports of hydrogen derivatives or chemical carriers, such as ammonia, from Texas into the global market.

Water Policy Implications in Texas

The emerging hydrogen economy in Texas is but one dimension of a mounting, statewide need for a cohesive, holistic approach to water resource development. Water resource development must inherently involve a stack of solutions, with specialization at the regional scale to capitalize on whatever combination of resources (e.g., groundwater, surface water, underutilized effluent and/or industrial discharges, etc.) are most readily available. The state has a unique, timely, and time sensitive opportunity to catalyze development of water resource development strategies, in particular: upstream process water reuse and large-scale seawater desalination.

Oil and gas operations in Texas use and dispose nearly 4 billion barrels[127] of produced water per year. Capacity constraints on produced water disposal impact energy production, either indirectly by changing project economics or directly through production curtailments. While upcycling of produced water is technically, logistically and statutorily challenging, any reuse of produced water resources for non-potable applications offsets pressure on other water resources; this is a uniquely Texas opportunity, which, if realized with optimized logistics by way of centralized infrastructure and process integration to minimize transport distances, could constitute an economic opportunity.

Marine seawater desalination, with a direct physical connection the Gulf of Mexico for both intake feedstock and effluent (brine) discharge, presents a truly scalable water resource development

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[124] Railroad Commission of Texas, Pipeline Safety.

[125] The Daily Jeff, https://www.daily-jeff.com/story/news/2013/05/01/two-thirds-states-are-almost/18942962007/.

[126] Texas Nat. Res. Code § 111.002.(6).

[127] Texas Produced Water Consortium, Beneficial Use of Produced Water in Texas: Challenges, Opportunities and the Path Forward, p. 12.

opportunity. In 2023, the Texas Legislature dedicated one billion dollars of general revenue to support water resource development at scale by way of the Texas Water Fund, to be administered by the Texas Water Development Board. Large scale (100MGD +) desalination facilities—if sited in strategic locations along the Texas coast guided by state policy or direct investments—could anchor a systematic, state-wide strategy for addressing mounting water demand over time, including alleviating feedstock limitations in bringing electrolytic hydrogen production to scale (or process water limitations that may otherwise constrain methane reformation at scale). Process synergies between micro and/or small modular nuclear and desalination are well documented; the potential integration and co-location of these complementary processes with hydrogen production may yield compelling economics that could further differentiate Texas as a global leader of low-carbon hydrogen at scale.

International Policy Considerations for Texas

More than 130 countries have set or are considering a target of net-zero emissions by 2050. Global demand for hydrogen could reach 540 MTPA in 2050 based on policy and regulatory drivers, especially in Europe and Asia.[128] International trade (imports/exports) of hydrogen is expected to account for twenty percent of global hydrogen and hydrogen-based fuel in 2050.[129] With Texas as a low-cost global leader in hydrogen supply, this opens a very important export market, particularly for ammonia and methanol, 'drop-in' fuels that are expected to represent most of the global export market for clean hydrogen. Consequently, numerous large, or even world scale, ammonia plants are advancing through commercial milestones on the Texas coast, including sites in Corpus Christi, Houston, Port Lavaca and Port Arthur.

Japan, South Korea, and parts of Europe are expected to be the first importers of hydrogen, and indeed power generation companies may be both off-takers and equity partners in Texas ammonia plants. North Asian markets, in particular, seem initially focused on using low-carbon ammonia to help decarbonize legacy coal-fired power plants that cannot yet be decommissioned. The scale of this North Asian demand is such that blue hydrogen will be required, and Japanese and South Korean markets are notably less fixated on renewable (green) hydrogen than European counterparts.

State policy that facilitates direct foreign investment in Texas—or, at a minimum, avoidance of policy that intentionally or unintentionally inhibits such investment—will allow Texas to leverage associated investments in cornerstone hydrogen delivery infrastructure.

Texas' State Policy Considerations

Recommendation 10: Texas' state policy to support the hydrogen industry should be designed to maximize economic benefits for its citizens while minimizing costs for taxpayers. This can be achieved by:

1. *leveraging federal incentives, minimizing the need for state incentives,*
2. *maintaining a business-friendly environment with efficient permitting processes and property tax abatements to support world scale, strategic projects,*
3. *fostering industry development that creates hydrogen demand, focusing on targeted, high-impact end-uses, and*

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[128] The Center for Houston's Future, Greater Houston Partnership, Houston as the Epicenter of a Global Clean Hydrogen Hub, p. 19.
[129] IEA, Global Hydrogen Review 2021, p. 161.

(4) *aligning production with international standards, which will enhance Texas' potential as a global exporter of clean energy, hydrogen products and hydrogen derivatives.*

With considerable policy support for clean hydrogen from the U.S. federal government and international support from European, Japanese, and South Korean markets, Texas can craft state policies that maximize the benefit to Texas citizens while minimizing the cost to the Texas taxpayer. Texas is well positioned to take advantage of:

1) International policy incentives, taxes, and mandates creating a significant demand pull for clean, low-cost hydrogen and hydrogen derivatives (i.e., ammonia),
2) U.S. incentives creating an impetus for global clean hydrogen production to be based in the U.S., and
3) Competitive advantages in the state creating an impetus for U.S. clean hydrogen production to be based in Texas, with low-cost energy, pipeline and port infrastructure, clean electricity, CCS infrastructure and other advantages discussed throughout this report.

Exponential development in the hydrogen industry within the state is possible by:

1) Leveraging the numerous grant and tax credit opportunities made available at the federal level for projects within Texas,
2) Maintaining a business environment which fosters growth, with efficient permitting and property tax abatement opportunities to support strategic, world scale projects,
3) Fostering industry development which creates hydrogen demand, focusing on targeted, high-impact end-uses (such as ammonia, clean steel, biofuels, aviation, shipping and mobility), and
4) Aligning production with international standards, which will maximize Texas' potential as a global exporter of clean energy and products supported by hydrogen and hydrogen derivatives.

This approach aligns with Texas' historical precedent as a hydrogen leader and takes full advantage of funding and international demand to foster significant investment and economic growth across the state.

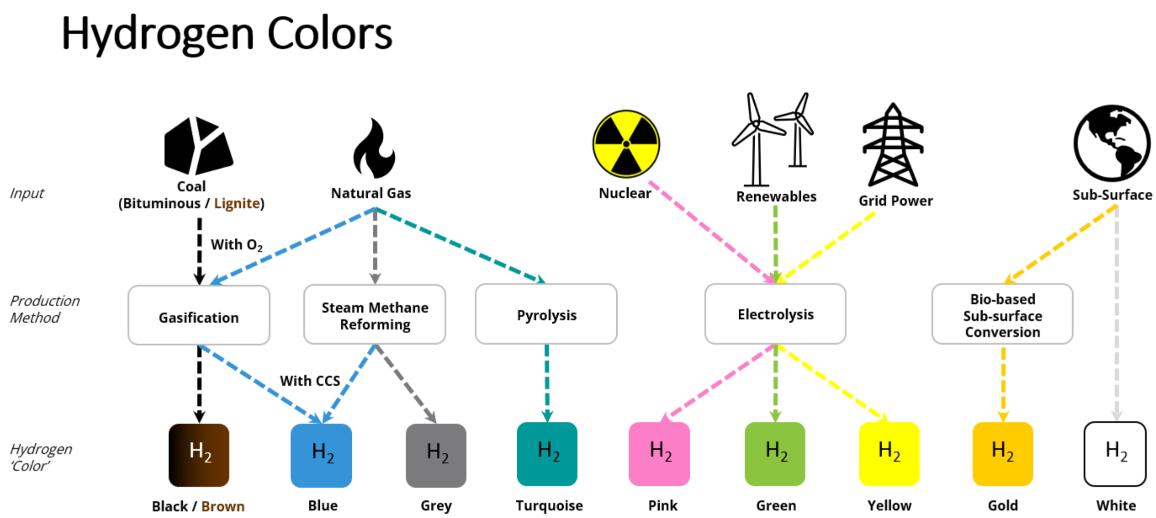
Conclusion

The hydrogen industry is poised to expand exponentially over the next few decades, driven by demand from various sectors focused on clean energy and manufacturing. Texas' leadership in the global hydrogen industry provides substantial advantages, creating significant opportunities for investment, job creation and economic growth. To capitalize on this immense potential, Texas should make minor adjustments to enhance its already robust framework of regulatory oversight, ensuring that the hydrogen industry continues its long track record of excellence in safety and environmental stewardship. To retain and expand its leadership position in the hydrogen industry, Texas must support the critical enablers of hydrogen production, transportation, storage and demand. To sustain this momentum, Texas policymakers, industry experts and community leaders must collaborate to continue this momentum and achieve a shared vision of Texas as the epicenter of the hydrogen industry, now and in the future.

Appendix I: Hydrogen Carbon-Intensity is More Important than Color

Throughout this report, references to different colors of hydrogen are made as a concession to the prevailing lexicon that describes different hydrogen production technologies. The hydrogen resulting from these different production methods is fungible, with absolutely no difference in performance or physical characteristics.

Figure 3: Hydrogen Colors by Production Method



Source: Kurtz, Preston.

The reliance on colors to describe hydrogen is unfortunate because a much better measure for determining "clean" hydrogen is to identify the "carbon intensity" of its production pathway, which may include not only the production technology, but the carbon footprint of the raw material used for the hydrogen production (natural gas, biomass, landfill gas, water/electrolysis, etc.). Carbon intensity is an objective measure of carbon footprint, represented by the kilograms of CO_2 or CO_2 equivalent emissions generated per kilogram of hydrogen produced.

Assigning a color with an inferred relative "cleanliness" to hydrogen based on the method by which it was produced is problematic for a variety of reasons:

- It may fracture hydrogen markets along production boundaries.
- Sub-optimal systems may be "locked-in"
- It can stifle innovation by boxing-out innovative solutions
- It is deeply inaccurate.

The final point is illustrated in a study published by UC-Davis's Institute of Transportation Studies (ITS) which compiled systematic results from 85 separate Studies, representing 387 Carbon Intensity values collected from 12 different hydrogen production methods.[130] The analysis revealed significant variability in carbon intensity, even from the same production methods, depending on the production "pathway".

[130] Busch, Kendall, Lipman, A systematic review of life cycle greenhouse gas intensity values for hydrogen production pathways.

The ITS study highlighted the need to assess hydrogen production pathways individually, considering feedstock, energy source, and conversion technology.

In any context in which Texas seeks to distinguish hydrogen by its relative emissions, it is recommended that it focus, like the DOE, on carbon intensity, and not on the colors of hydrogen. This approach maintains technology neutrality and encourages broad innovation in the methods of hydrogen production, which ultimately leads to cleaner, lower cost hydrogen production.