Houston as the epicenter of a **global clean hydrogen hub**

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CENTER FOR HOUSTON'S FUTURE

GREATER HOUSTON **PARTNERSHIP**

HOUSTON ENERGY TRANSITION INITIATIVE

Acknowledgement

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We are extremely grateful for the input of a working group of more than 100 individuals from 70 companies and organizations along the hydrogen value chain who worked collaboratively to develop a shared vision for Houston's role as a clean hydrogen hub. This vision for how the Houston region and the state of Texas can lead the nation and the world in the quest for addressing climate change could not have been developed without their dedication, expertise, and enthusiasm.

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Preface

This report is the result of work by the Houston Energy Transition Initiative's (HETI) Hydrogen Working Group, a collaboration organized by the Greater Houston Partnership (GHP) and the Center for Houston's Future (CHF) to develop a shared vision for how the Houston region and the state of Texas can lead the energy transition.

HETI seeks to leverage Houston's energy leadership to accelerate global solutions for a low-carbon future. HETI's objective is to create a vision and a blueprint for growing the region's economy, exporting low-carbon products and expertise, equitably creating new jobs, and helping Houston achieve the goals of its Climate Action Plan.

The report examines one aspect of that goal: the viability of a Houston-led clean hydrogen regional hub and describes what the state could achieve in terms of scale, cost, and diversity of projects over time.

The Department of Energy (DOE) defines a regional clean hydrogen hub as "a network of clean hydrogen producers, potential clean hydrogen consumers, and connective infrastructure located in close proximity."[1] In addition, in the recently passed Infrastructure Investment and Jobs Act, Congress defined "clean hydrogen" as hydrogen production that meets specific CO_2 emissions targets.[2] Consistent with these definitions, this report focuses on building a view of the physical clean hydrogen value chain in Texas, including competitive advantages and unlocks required to drive the creation of the hub. More specifically, the report discusses the supply of and the demand for clean hydrogen in Texas and offers a vision and a roadmap for how a hydrogen ecosystem led by Houston could develop.

This report presents a baseline view of clean hydrogen in Texas, reflecting a shared understanding of the potential among several players across the value chain. This view has been iteratively co-developed and incorporates inputs from members of the Hydrogen Working Group.

The report demonstrates how Houston can become a true hydrogen economy, which will require markets, infrastructure, pricing, carbon trading, and risk management. Such an ecosystem will be transformative by enabling participants across different value chain segments to drive innovation.

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[1] *DOE Update on Hydrogen Shot, RFI Results, and Summary of Hydrogen Provisions in the Bipartisan Infrastructure Law*, U.S. Department of Energy, December 8, 2021. Retrieved from: https://www.energy.gov/sites/default/files/2021-12/h2iq-12082021.pdf

[2] *H.R.3684 - Infrastructure Investment and Jobs Act*, U.S. Congress website, November 15, 2021. Retrieved from: https://www.congress.gov/bill/117th-congress/house-bill/3684/text

In addition, the report examines four cross-cutting enablers: policy,[3] infrastructure, innovation, and talent. The report concludes with a synthesis of this effort and highlights areas to explore further in subsequent work. Finally, the appendix provides additional details on the assumptions, tools, and references used in this analysis.

The intended audience for the report includes members of the business community, non-profits, academic institutions, policymakers, and other organizations with an interest in Houston's future clean hydrogen economy. The report is organized for both linear flow and modularity: Readers can choose to focus on a specific chapter without having to reference earlier chapters.

The report discusses statistics, forecasts, and other figures obtained from publicly available sources, companies in the hydrogen working group at the Center for Houston's Future, and interviews with subject matter experts. Estimated costs of hydrogen production, storage, and transport are context specific and reflect a particular set of conditions. The analysis is cost-based and excludes profit margin; 2020 was used as a starting point because this year represents the most complete and accurate data available at the time of writing.

The report attempts to clearly delineate inclusions and exclusions for these estimates where relevant. Therefore, any attempt to compare estimates in this report with other published data on clean hydrogen production costs, for example, must take the specific context and assumptions into account.

While this report primarily focuses on achieving the emissions and cost targets required to develop a clean hydrogen hub, more work is required to ensure that the benefits of a clean hydrogen hub flow to all communities. Achieving outcomes that support environmental justice, create good jobs, and incentivize U.S-based manufacturing are all core to the vision of a successful clean hydrogen hub in Texas. While much of this work is still in development, the report references many evolving efforts to build the hydrogen economy, including several key environmental justice, workforce, and other initiatives that will be integral to the clean hydrogen vision and roadmap.[4]

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[3] While this report addresses policy and focuses on the economics of hydrogen demand and production, it does not take an advocacy stance. This is an area where additional work is warranted, and there are several efforts currently underway.

[4] For example, the City of Houston has launched Complete Communities and Resilient Houston to support equity initiatives in under-resourced communities.

“We meet at a college noted for knowledge, in a city noted for progress, in a State noted for strength, and we stand in need of all three, for we meet in an hour of change and challenge, in a decade of hope and fear, in an age of both knowledge and ignorance. ...[T]his city of Houston, this State of Texas, this country of the United States was not built by those who waited and rested and wished to look behind them. This country was conquered by those who moved forward....”

President John F. Kennedy

Moonshot Speech, Rice University
September 12, 1962

“Clean energy takes all kinds of forms into the future, and Texas can be a leader. (Houston) powered the past and we want [Houston] to power the future.”

“This is our generation’s Moonshot.”

Jennifer Granholm

U.S. Energy Secretary
April 23 and June 1, 2021

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1 Executive summary

Around the globe, governments are recognizing the importance of clean hydrogen in building an energy system to reach net-zero carbon emissions. As of October 2021, 17 governments had published hydrogen strategies and more than 20 were in the process of developing strategies.[1] The U.S. Department of Energy (DOE) has declared clean hydrogen crucial to achieving President Biden's goals of a 100% clean electrical grid by 2035 and net-zero carbon emissions by 2050.[2]

The current economics of clean hydrogen production and distribution do not currently support large-scale adoption by customers to replace lower-cost, higher-carbon-intensity alternatives. Regional hydrogen hubs have the potential to accelerate the scaling of hydrogen through concerted development of demand, supply, and infrastructure. But policy interventions will be required to drive down costs and incentivize the adoption of clean hydrogen.

A Houston-led clean hydrogen hub could have sizeable and lasting impact on the region. Based on the estimated potential, the economic, environmental, and social benefits in 2050 could be substantial, fundamentally shaping the long-term vision of the hydrogen hub.

Exhibit 1

Vision for Texas as a hydrogen hub, 2050 snapshot

Global leader in hydrogen production, use, innovation, talent development, equity and justice

21MT of clean hydrogen production in Texas, including 11MT local demand, 10MT export

180k potential direct, indirect, and induced jobs to be created in the hydrogen economy

$100B potential addition to Texas' GDP, i.e., 6% of Texas' 2019 GDP

220MT Global CO$_2$ abatement potential from 21MT of hydrogen

Sources: U.S. Bureau of Economic Analysis, McKinsey estimates

This vision rests on an assessment of the clean hydrogen value chain, including both supply and demand, and sample projects. Realizing the vision will require implementing a core set of enablers. Key findings across these topics are summarized below:

Supply

- **Many factors give Texas significant advantages on the cost and capacity of hydrogen production** such as abundant renewable power generation and low-cost natural gas, existing hydrogen production capacity, favorable geological formations for storing hydrogen and CO$_2$, and local demand drivers, as well as top-caliber academic research and industry-led innovation.
  - **Texas already benefits from access to renewables and natural gas**, with Texas producing more wind-powered generation and natural gas than any other state.[3]
  - **Clean hydrogen production costs in Texas could improve** from 2022 to 2050, with electrolysis-based hydrogen cost decreases attributable primarily to lower renewable costs and electrolyzer system capital expenditures

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[1] *Global Hydrogen Review 2021*, IEA, October 2021. Retrieved from: https://www.iea.org/reports/global-hydrogen-review-2021

[2] *DOE Establishes Bipartisan Infrastructure Law's $9.5 Billion Clean Hydrogen Initiatives*, Department of Energy, February 2022. Retrieved from: https://www.energy.gov/articles/doe-establishes-bipartisan-infrastructure-laws-95-billion-clean-hydrogen-initiatives

[3] *Texas State Energy Profile Overview*, EIA, April 2021. Retrieved from: https://www.eia.gov/state/?sid=TX

(capex), and natural-gas-based hydrogen cost decreases attributable to system efficiency gains and capex reductions.

  - **The estimated cost of producing natural-gas-based hydrogen with carbon capture and storage (CCS) in 2030 could meet the DOE's goal of $1/kg of clean hydrogen**; however, electrolysis-based hydrogen is unlikely to achieve this target without government interventions in the form of research and development funding or direct incentives for hydrogen production and supporting technologies, such as renewables and CCS.

- **Texas has natural advantages in developing cost-effective hydrogen transport and storage**, given its extensive oil and gas and hydrogen pipelines, experience in hydrogen storage, salt caverns, and developed port infrastructure.

- **The Gulf Coast is positioned to be the center of a clean hydrogen U.S. export hub,** given its ability to potentially compete with likely major exporters (e.g., Australia, Chile, and Saudi Arabia) on the delivered cost of hydrogen by leveraging its cost advantages and significant port infrastructure. Several strategic considerations (e.g., security, reliability, and capacity) also provide advantages.

Demand

- **While global clean hydrogen demand is limited today, it is expected to grow 6-8% each year on average between 2030-50.** Hydrogen is expected to play a critical role in decarbonizing sectors such as industry, mobility, and power – potentially addressing 660 million tons (MT) of worldwide demand by 2050, according to the Hydrogen Council.[4]

- **Demand for clean hydrogen in Texas could reach 21 MT by 2050** – compared to current demand of 3.6 MT for conventionally produced hydrogen. The expected demand in 2050 comprises 11 MT for local demand and a surplus of 10 MT for export.
  - **Export of hydrogen and hydrogen-based fuels is the largest driver of the increase,** contributing ~10 MT of hydrogen demand.
  - **Industrial applications are the second largest driver,** with feedstock and heating in sectors such as refining, petrochemicals, ammonia, iron and steel, and cement accounting for ~6 MT of hydrogen demand.
  - **Mobility is the third largest driver** with ground transportation (trucks, light commercial vehicles, and buses) accounting for ~2.3 MT of hydrogen demand and marine and aviation accounting for ~1.5 MT of hydrogen and hydrogen-based fuel demand.
  - **Utility power generation is the fourth largest driver** with energy storage and local grid natural gas blending accounting for ~1.6 MT of hydrogen demand.

Vision and strategic roadmap

- **The proposed 2050 vision could have massive impact on climate, jobs, and the economy,** including an estimated 220 MT of global CO_2 abatement, $100 billion in economic value, and the creation of 180,000 jobs.

- **With the right supportive policy frameworks, Texas with Houston at its core could become the global leader in clean hydrogen production, application, development, and exports;** the resulting thriving hydrogen community could push innovation and develop the necessary talent to conceive and deliver hydrogen projects.

- **Realizing the 2050 vision requires a multiphase roadmap.** Phase 1 (2022-25) should jumpstart a vibrant ecosystem while advocating for regulatory and policy incentives. Phase 2 (2025-30) should decarbonize existing applications while exploring new ones. In Phase 3 (2030-35), the hub should seek to achieve the target of $1/kg of clean hydrogen while further scaling local demand and export in Phase 4 (2035-50).

- **Texas could substantially improve** social and environmental conditions for all communities, **especially by focusing on environmental justice (EJ)** for disadvantaged communities affected by industrial pollution. This is an opportunity to better serve those residents who might be disproportionately impacted by poor air quality and other environmental factors.

Sample projects

- As the clean hydrogen ecosystem develops, a variety of projects addressing supply, demand, and infrastructure might spread across the state, concentrated in areas around Greater Houston, Corpus Christi and South Texas, Dallas and the Texas Triangle, Beaumont and East Texas, and West Texas.

- **The hub structure would enable**

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[4] *Hydrogen for Net-Zero*, Hydrogen Council, McKinsey & Company, November 2021. Retrieved from: https://hydrogencouncil.com/wp-content/uploads/2021/11/Hydrogen-for-Net-Zero.pdf

an integrated ecosystem, which balances supply, demand, and infrastructure needs. Achieving an end-to-end balance would require an orchestrated approach by participants across the clean hydrogen value chain.

Cross-cutting enablers

- **Government commitments, direct incentives, and regulatory frameworks are the major policy instruments** for decreasing cost and increasing demand. In addition to federal policies, Texas should implement state-level policies to accelerate progress toward realizing the 2050 vision. This report provides an initial view on policy topics. More work is needed to flesh out the appropriate options.
- **Scaling hydrogen will require developing infrastructure,** including hydrogen transport and storage, fueling stations, CO_2 transport and storage, water purification and transportation, electricity transmission, port infrastructure, and a mature supply chain for critical materials.
- **The hub would benefit from a vibrant innovation ecosystem,** including a research consortium that fosters collaboration across institutional lines, a joint-venture/start-up network that leverages existing assets and demand in the region, a testing facility to scale and commercialize new technologies, and local equipment manufacturing.
- **Meeting the hub's talent needs would require implementing equitable workforce development programs.** Community colleges, institutions of higher education, and companies could all play key roles in training the workforce for the hydrogen economy.

Next steps

The next phase of this work will build on the findings presented in this report to develop a demand-centric roadmap for 2022-2030. More specifically, the next phase will identify the sectors that are ready to respond to net-zero-driven demand signals for clean hydrogen and to projects that can meet demand via a network of supply, shared infrastructure, and storage. This phase will also explore hub funding requirements, sector-specific legal and regulatory unlocks, and ways to build the right coalition for an integrated effort to develop the hydrogen hub. Collectively, these actions will create the blueprint for Houston to navigate the energy transition and continue thriving as the energy capital of the world.

2 Supply

Clean hydrogen production might emerge along various pathways, including electrolysis, natural gas reforming, and methane pyrolysis. These types of hydrogen are often depicted as colors, e.g., green, blue, and turquoise. **However, the primary determinants of any pathway's adoption are the cost and carbon intensity of hydrogen production.** These factors would determine Texas' ability to compete economically and environmentally on the world stage as it seeks to become a clean hydrogen hub.

This report is technology-agnostic on hydrogen production but focuses primarily on **electrolysis-based**[1] **and natural-gas-based production pathways** to illustrate the magnitude of potential cost reductions over time and the competitiveness of Texas' clean hydrogen production.

1. Global cost trajectory

Significant cost reductions in clean hydrogen production over the next 30 years could fuel global adoption of hydrogen.

Electrolysis-based hydrogen production costs on average could drop significantly by 2030.[2] This cost reduction would be due primarily to the expected decrease in capex costs, as well as the scaling of electrolyzer systems. Other factors in production costs include continued advancements in renewable energy, i.e., falling levelized cost of energy (LCOE) and increasing capacity factors.[3]

Natural-gas-based hydrogen production costs could also fall in the coming years. Steam methane reforming (SMR) is the dominant technology for creating hydrogen from natural gas. However, other technologies exist such as autothermal reforming (ATR), a type of natural-gas reforming technology with natural gas as feedstock. Carbon capture equipment can be added to both technologies. Carbon capture rates for SMR and ATR have improved, further reducing emissions; and the cost to capture each ton of carbon dioxide is expected to drop. ATR may be adopted more widely in the future due to the low carbon intensity of its hydrogen production, but SMR will likely remain common due to its current market share.

Several emerging technologies for producing hydrogen (e.g., methane pyrolysis, synthetic biology, and photocatalysis) might also develop. This report acknowledges that some of these technologies could become economically attractive and contribute to future hydrogen supply.

For the purposes of developing a detailed economic view, this report focuses on the two clean hydrogen pathways currently projected to provide the largest share of supply in Texas.

2. Texas' current cost of supply advantages

Texas currently produces 3.6 million tons per annum (MTPA), or a third of the country's total annual hydrogen production.[4]

Texas enjoys **abundant natural resources** (e.g., wind and natural gas), **existing infrastructure** (e.g., the largest network of hydrogen pipelines in the U.S.), **favorable geological formations** for storing hydrogen and CO_2 (e.g., salt caverns and saline formations onshore and offshore), significant and **concentrated industry demand** (e.g., refining and petrochemicals along the U.S. Gulf Coast), and a **highly skilled workforce** (e.g., oil and gas and manufacturing expertise) – all of which could support hydrogen production from both **electrolysis-based and natural gas-based pathways.**

Abundant natural resources: West

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[1] For the purposes of this paper, electrolysis-based is defined as hydrogen produced using renewable energy, i.e., this excludes hydrogen produced via electrolysis using nuclear power and other sources of energy.

[2] *Hydrogen Insights Report 2021*, Hydrogen Council, McKinsey & Company, July 2021. Retrieved from: https://hydrogencouncil.com/en/hydrogen-insights-2021/

[3] *Hydrogen Insights Report 2021*, Hydrogen Council, McKinsey & Company, July 2021. Retrieved from: https://hydrogencouncil.com/en/hydrogen-insights-2021/

[4] *Texas could become nation's leader in production of hydrogen energy*, Houston Chronicle, February 2021. Retrieved from: https://www.houstonchronicle.com/business/texas-inc/article/Texas-could-become-nation-s-leader-in-15941151.php

Hydrogen Production, U.S. Department of Energy, Retrieved from: https://www.energy.gov/eere/fuelcells/hydrogen-production

Texas enjoys some of the strongest, sustained wind speeds in the country, allowing Texas to produce abundant and cheap renewable wind energy. Texas produces the most wind-powered generation in the United States.[5] This gives Texas a strong advantage in producing clean hydrogen through electrolysis, as electricity is the single largest cost driver.

West Texas does not have easy access to water, but the cost savings from abundant and reliable wind are far larger than the cost of transporting water to the region. For example, increasing the cost of water five-fold (from, say, \$0.50/m³ to \$2.50/m³) increases the total cost of hydrogen by less than 1%.[6]

The United States enjoys some of the lowest natural gas prices in the world. Furthermore, Texas has cheaper natural gas than the rest of the country. According to the U.S. Energy Information Administration (EIA), the price of natural gas used by power producers in Texas has been ~9% lower than the rest of the country since the EIA started tracking this data in 1997.[7] Low prices give Texas a substantial competitive advantage since natural gas is the largest cost component in producing hydrogen from natural-gas-based pathways.

Existing infrastructure: Pipelines are the most economical means of transporting hydrogen locally and regionally, while transportation by sea is more competitive for transcontinental distances.[8]

Exhibit 2

Texas enjoys many advantages in scaling up hydrogen production

General

- Proximity to demand favorable to driving early adoption
- Welcoming environment for infrastructure development
- Existing hydrogen capacity and expertise
- Environmental justice impact
- Concentration of academic and industry-driven innovation
- Highly skilled workforce

Production capacity and cost

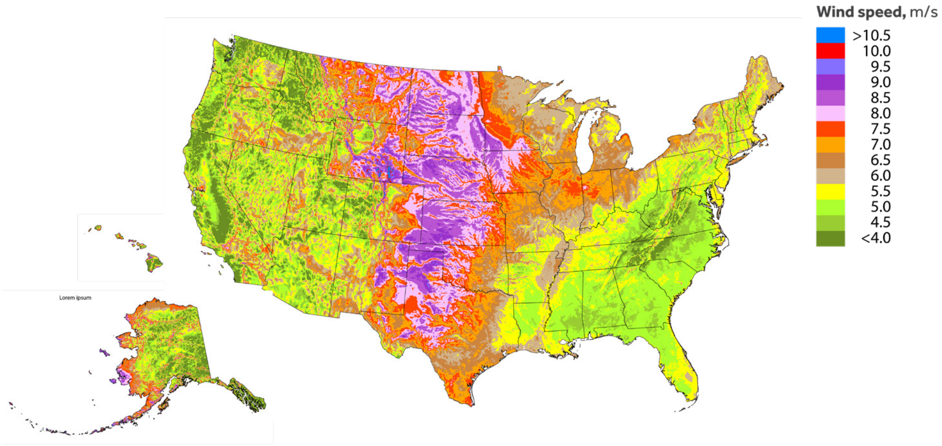
- Access to low-cost renewable energy capacity
- Access to CO_2 storage locations
- Access to low-cost natural gas

Transportation and storage

- Largest network of hydrogen pipelines in the US
- Access to geologic formations for seasonal storage

Exhibit 3

Annual average wind speed in the United States[9]



The Texas Gulf Coast has access to 900 miles of hydrogen pipelines, accounting for more than half of all hydrogen pipelines in the United States and one-third of the world's total.[10] Unlike natural gas pipelines, which allow open access,

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[5] *Texas: State Profile and Energy Estimates*, U.S. Energy Information Administration, April 15, 2021. Retrieved from: https://www.eia.gov/state/?sid=TX

[6] Assuming ~85 MW alkaline electrolyzer system

[7] *Texas Natural Gas Prices*, U.S. Energy Information Administration. Retrieved from: https://www.eia.gov/dnav/ng/ng_pri_sum_dcu_stx_a.htm

[8] *Global Hydrogen Demand Outlook 2021*, IEA, October 2021. Retrieved from: https://www.iea.org/reports/global-hydrogen-review-2021

[9] *U.S. Average Annual Wind Speed at 80 Meters*, U.S. Department of Energy. Retrieved from: https://windexchange.energy.gov/maps-data/319

[10] *Houston: The Low-Carbon Energy Capital*, University of Houston, October 2020. Retrieved from: https://uh.edu/uh-energy/symposium-archives/2020-2021/low-carbon-energy-capital/

HyBlend: Opportunities for Hydrogen Blending in Natural Gas Pipelines, U.S. Office of Energy Efficiency & Renewable Energy, June 2021. Retrieved from: https://www.energy.gov/eere/fuelcells/hyblend-opportunities-hydrogen-blending-natural-gas-pipelines hydrogen pipelines are not regulated by the Federal Energy Regulatory Commission (FERC) and provide only "bundled" sales and transportation via bi-lateral contracts between the pipeline owners/operators (primarily large, industrial gas companies) and their industrial clients. This existing infrastructure points to a competitive advantage in the form of knowledge and expertise with respect to hydrogen pipelines. Texas also has one of the nation's most extensive networks of natural gas pipelines, which can potentially be repurposed to transport hydrogen.

Favorable geological formations: The Texas Gulf Coast also has salt caverns that can store hydrogen and carbon dioxide for extended periods of time. Texas has three of the four operational salt caverns in the world used for hydrogen storage. ConocoPhillips has been storing hydrogen in the Clemens Dome, about 850 meters underground, since 1983. Air Liquide stores hydrogen in Spindletop, the largest salt cavern on the Gulf Coast. Praxair uses the Moss Bluff salt cavern, which is connected to a hydrogen pipeline network. These caverns have working storage of 82 GWh, 278 GWh, and 125 GWh, respectively.[12]

The Gulf Coast region also has the largest saline formation capacity for storing CO_2 in the United States. This onshore and offshore capacity is estimated at one trillion tons, or the capacity needed to store 10,000 times Houston's current annual emissions.[14]

Exhibit 4

Existing hydrogen system in the Gulf Coast area[11]

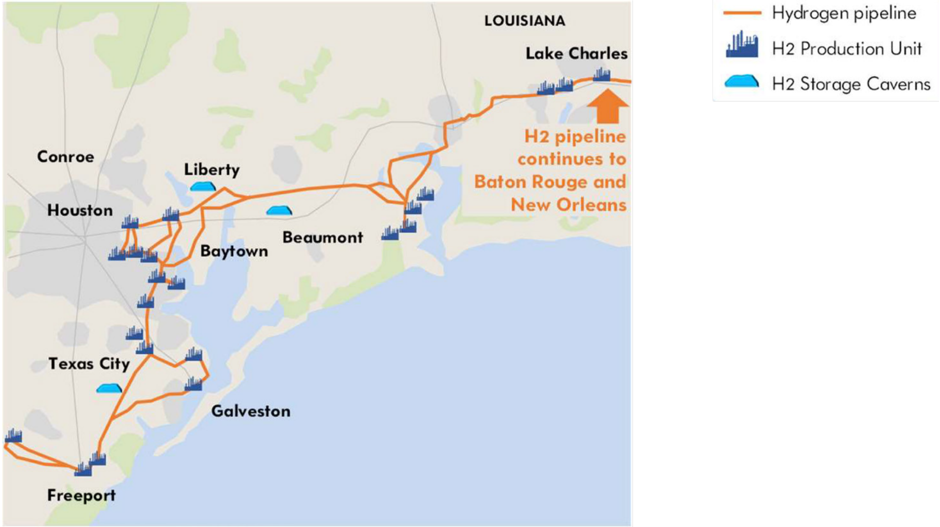
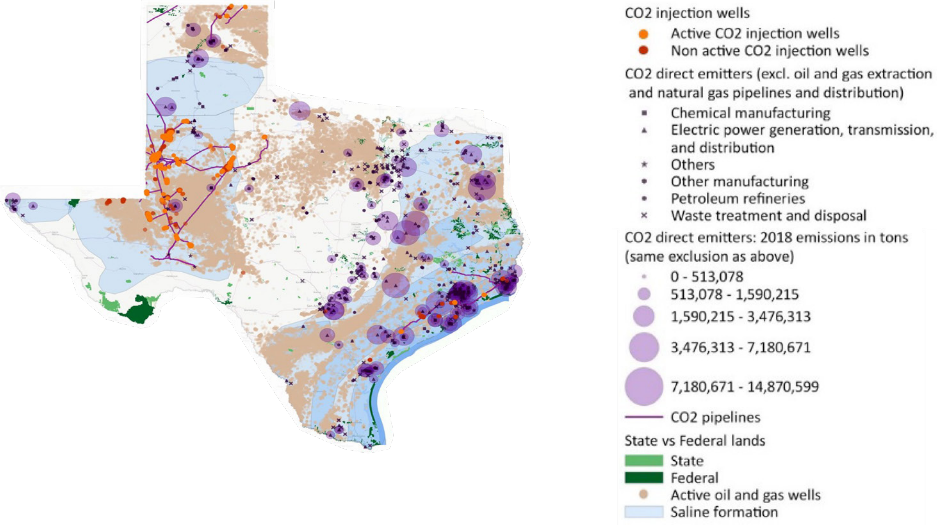


Exhibit 5

Composite map of the CO_2 storage capacity in saline formations and active oil fields in Texas[13]



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[11] *Energy Transition and the Houston Region: A New Vision*, Center for Houston's Future, April 2021. Retrieved from: https://www.h-gac.com/getmedia/babc5d55-8dcb-4ee2-824d-61b27bff6b96/04-09-21-Brett-Perlman-Center-for-Houston-s-Future-April-2021

[12] *Global Hydrogen Demand Outlook 2021*, IEA, October 2021. Retrieved from: https://www.iea.org/reports/global-hydrogen-review-2021

Comments by the Center for Houston's Future to the U.S. Department of Energy's Earthshot Request for Information, Center for Houston's Future, July 2021. See Appendix C for hyperlink

[13] *Expanding Carbon Capture in Texas*, Rice University's Baker Institute for Public Policy, January 2021, https://www.bakerinstitute.org/media/files/files/8e661418/expanding-ccus-in-texas.pdf

[14] *Evaluating Net-Zero Industrial Hubs in the United States: A Case Study of Houston*, Columbia University, Center on Global Energy Policy, June 2021. Retrieved from: https://www.energypolicy.columbia.edu/research/report/evaluating-net-zero-industrial-hubs-united-states-case-study-houston

Both Texas and the federal government have a role to play in developing offshore CO_2 storage. Texas is uniquely situated to take advantage of this capacity because it has jurisdiction over the first ten miles of shelf from its shoreline, while most states control only about three miles.[15] There is an opportunity to collaborate with the federal government in deeper offshore waters.

Concentrated industry demand: Texas is likely to be a demand hub for hydrogen given its high share of U.S. industrial activities and population growth, as seen in potential demand clusters such as Greater Houston, Corpus Christi, and the Texas Triangle. Proximity to demand could help hydrogen producers in the region drive early adoption.

Highly skilled workforce and advanced research: Texas boasts a highly skilled workforce and a sophisticated, in-state manufacturing network that could help build the needed infrastructure for the hydrogen economy at a competitive cost.

Texas also enjoys a high concentration of academic research and industry-driven innovation. An estimated 300 researchers at major Texas universities are working on hydrogen-related projects, and the state has more certified hydrogen pipeline inspectors than other states.

Given the abundance of workers' development programs and talent pipelines for the energy industry, Texas could readily deploy significant training and education to create jobs in clean hydrogen. These programs should continue to prioritize targeting disadvantaged communities.

3. Trajectory of Texas' cost of supply

The hydrogen value chain involves a complex set of components, regardless of the production pathway. Costs differ across the value chain, and any cost analysis must make **choices about what to include and what to exclude.** These choices help frame **which inputs** to include when calculating **hydrogen "cost of supply"** in Texas.

This report attempts to be explicit about which costs (e.g., capital expenditures and operating expenditures) are included or excluded and why. Comparison with other analyses, or analysis of a different project scope, might require adjusting this approach.

Additionally, the report takes a "modular" approach to examining costs discretely along the value chain, meaning that the analysis looks at production, transport, and storage costs separately.

A. Cost of production

Pathway #1: Electrolysis-based pathways

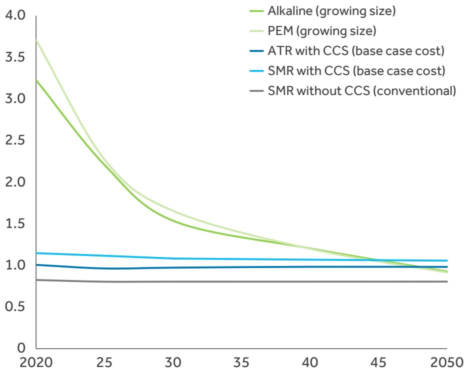
The primary technologies for producing hydrogen via electrolysis today include alkaline, proton exchange membrane (PEM) and solid oxide electrolyzer cell (SOEC). In 2020, alkaline accounted for ~60% of installed capacity and PEM accounted for ~30%.[16] SOEC and emerging technologies accounted for the rest.

Alkaline is a mature and durable commercial technology that does not use precious materials and is well suited for large-scale deployment (>10 MW) through 2030. PEM electrolyzers are capable of being used for large-scale deployments as well as smaller applications.

Exhibit 6

Texas hydrogen production economics from example pathways

Texas hydrogen production economics by technology, $/kg



Source: **McKinsey Hydrogen Insights**

Key assumptions

- **Hydrogen production costs exclude hydrogen transport and storage costs**
- **No carbon pricing or subsidies (e.g., PTC, 45Q) unless otherwise noted**
- **All pathways (including those not represented here) can play a role in developing Texas into a hydrogen hub. Alkaline and ATR were chosen as representative technologies to highlight Texas' cost advantages**
- **Hydrogen production costs include compression to 30 bar in capex**
- **Electrolysis-based hydrogen production assumptions:**
  - **Electricity cost** which uses the top quartile of TX wind (assumes co-location of renewables and production, i.e., no T&D costs): $28/MWh in 2020, $21/MWh in 2030
  - **For alkaline electrolysis:** assumes a system of ~2 MW in 2020, ~20 MW in 2025, and ~85 MW system in 2030-50
  - **For PEM electrolysis**: assumes a system of ~2 MW in 2020, ~20 MW in 2025, and ~85 MW system in 2030-50
- **Natural-gas-based hydrogen production assumptions:**
  - **Industrial electricity** prices average $0.07/kWh, natural gas costs between ~$2.5/MMBtu and ~$3/MMBtu from 2020 through 2050
  - **Capex:** includes capex for carbon capture but not transport or storage
  - **Opex:** CO_2 transportation and CO_2 storage is held constant at $6/ton and $10/ton, respectively; opex for carbon capture is included
  - ATR plant capacity = 500,000 Nm^3/h; SMR plant capacity = 100,000 Nm^3/h; ATR and SMR have carbon capture rates of 98% and 70%, respectively

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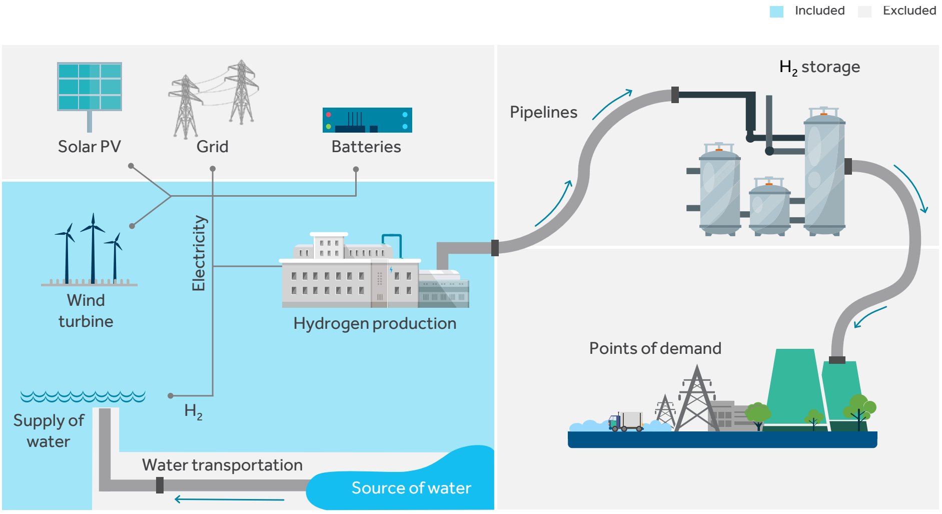
[15] *Evaluating Net-Zero Industrial Hubs in the United States: A Case Study of Houston*, Columbia University, Center on Global Energy Policy, June 2021. Retrieved from: https://www.energypolicy.columbia.edu/research/report/evaluating-net-zero-industrial-hubs-united-states-case-study-houston

[16] *Global Hydrogen Demand Outlook 2021*, IEA, October 2021. Retrieved from: https://www.iea.org/reports/global-hydrogen-review-2021

The bulk of this analysis focuses on alkaline electrolyzers due to their lower projected cost curves through 2030 compared to other electrolyzer technologies. (See Exhibit 6). In the long term, multiple electrolyzer technologies will play a key role in hydrogen production. PEM's current materials include platinum, iridium, and titanium—expensive materials subject to supply and price fluctuations.[17] SOECs operate at a very high temperature, allowing the system to run on relatively inexpensive nickel electrodes and use some of the heat to reduce the electricity demands of electrolysis.[18] Due to alkaline and PEM's majority share of the current and near-term market, along with lower cost curves, this report has focused on these technologies.[19] SOEC's will likely play a role in the future, particularly for use in industrial sites where waste heat is available.

Exhibit 7

Components of modeled electrolysis-based hydrogen production



The following analysis focuses exclusively on alkaline electrolysis as a technology representative of the broader electrolysis-based pathway. As individual projects come online, producers will likely evaluate site criteria, including the load profile of the local renewable electricity supply, to determine if batteries or alternative electrolyzer technologies would create the optimal production facility.

Inclusions/exclusions: The electricity cost in this analysis is based on the levelized cost of energy (LCOE) for onshore wind energy generation. This portion of the analysis assumes behind-the-meter wind generation and co-location of renewable energy generation with hydrogen production, i.e., no transmission and distribution costs of either electricity via wires or produced hydrogen via pipes. Those costs are discussed in section 2.3.B.

The analysis assumes that the hydrogen producer **will cover capital expenditures** (capex)that include the cost of the electrolyzer system, transport to site, balance of plant, installation and assembly, cost of building, and indirect costs (e.g., labor and admin). The producer's **operating expenditures** (opex) are assumed to include costs related to electricity, stack replacement, water,[20] and the purification, drying, and compression of hydrogen post-production.

This production analysis does not include the cost of transporting water to the site, transporting or storing hydrogen, optimizing power costs by utilizing both wind and solar, or using the grid or batteries to manage the intermittency of renewable energy sources. The analysis also does not account for subsidies when calculating production costs, unless stated otherwise for sensitivity analyses. Furthermore, the analysis does not assume any tax on carbon emissions.

By excluding these costs, the analysis highlights the production process, which allows for apples-to-apples cost comparisons across production estimates for different years and regions.

Inputs: The single greatest cost in electrolysis-based hydrogen production is the cost of electricity, which is represented by LCOE in this analysis. This report estimates that the average LCOE of wind without the Production Tax Credit (PTC) in Texas[21] could drop from $28/MWh in 2020 to $21/MWh in 2030, with continuous decline in wind capex.

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[17] *Water Electrolyzers and Fuel Cells Supply Chain*, U.S. Department of Energy, February 24, 2022. Retrieved from: https://www.energy.gov/sites/default/ files/2022-02/Fuel%20Cells%20%26%20Electrolyzers%20Supply%20Chain%20Report%20-%20Final.pdf

[18] *Green hydrogen cost reduction: Scaling up electrolysers to meet the 1.5°C climate goal*, IRENA, December 2020. Retrieved from: https://www.irena.org/publications/2020/Dec/Green-hydrogen-cost-reduction

[19] *Global Hydrogen Review 2021*, IEA, October 2021. Retrieved from: https://www.iea.org/reports/global-hydrogen-review-2021

[20] Water is assumed to be potable; no on-site purification is assumed

[21] Represents system average rather than cost for the best wind projects in Texas

The analysis also assumes a capacity factor of 46% in 2020 and 51% in 2030 with a growing electrolyzer system of ~ 2MW in 2020 to ~20 MW in 2025 to ~85 MW in 2030 through 2050. This scenario's LCOE incorporates the top quartile of Texas' wind speed, which is primarily wind resources in West Texas.

Outputs: Based on these assumptions, the analysis predicts that the cost of electrolysis-based hydrogen in Texas could be ~$3.2/kg in 2020, ~$1.5/kg in 2030, and ~$1./kg in 2050.

Sensitivity to changes in LCOEs

However, considering that inputs are subject to change, the analysis takes into account the possibility of higher LCOEs for Texas in order to offer a range of potential electrolysis-based hydrogen production costs.

To do so, the analysis uses two Texas-specific scenarios: Scenario A (high LCOE) and Scenario B (low LCOE).

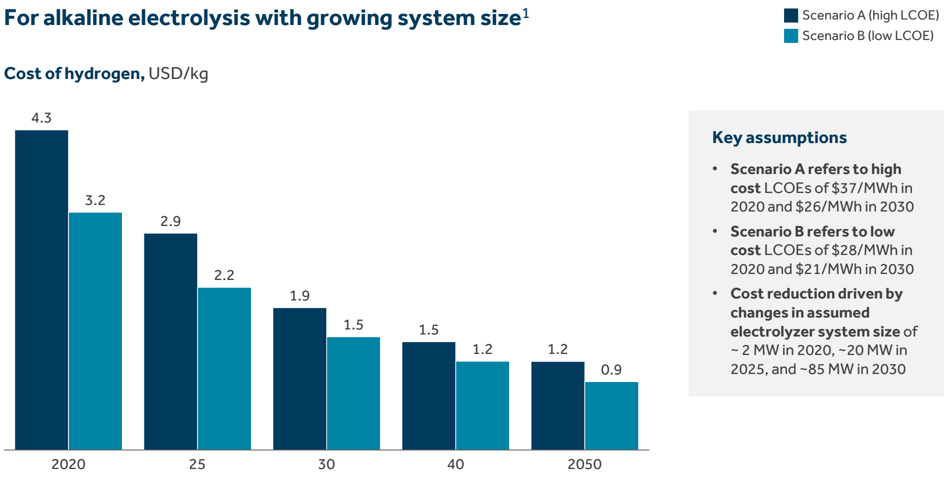
Scenario A estimates that the average LCOE of wind without PTC in Texas could be ~$37/MWh in 2020 and ~$26/MWh in 2030. The capacity factor is assumed to be 34% in 2020 and 39% in 2030 with the same growing electrolyzer system as in the low-LCOE scenario. This scenario's LCOE reflects a general average of all Texas' wind speed.

Exhibit 8

Potential hydrogen production costs, 2020-50

For alkaline electrolysis with growing system size[1]

Cost of hydrogen, USD/kg



Key assumptions

- **Scenario A refers to high cost** LCOEs of $37/MWh in 2020 and $26/MWh in 2030
- **Scenario B refers to low cost** LCOEs of $28/MWh in 2020 and $21/MWh in 2030
- **Cost reduction driven by changes in assumed electrolyzer system size** of ~ 2 MW in 2020, ~20 MW in 2025, and ~85 MW in 2030

1. Growing size is defined as using electrolyzer system size of ~ 2 MW in 2020, ~20 MW in 2025, and ~85 MW in 2030 through 2050
Source: McKinsey Hydrogen Insights

For Scenario B, the assumptions are the same as before with LCOEs of $28/MWh in 2020 and $21/MWh in 2030 and a capacity factor of 46% in 2020 and 51% in 2030.

Output[22]**:** Texas' electrolysis-based hydrogen production costs could range from ~$3.2 to ~$4.3 / kg in 2020 and ~$1.5 to ~$1.9/ kg in 2030. These reductions are attributable largely to declining costs for renewable wind energy, further reductions in the cost of electrolyzer systems, and the assumed increase in electrolyzer system size from ~2 MW in 2020 to ~20 MW in 2025 to ~85 MW in 2030 through 2050. Increasing system sizes were used to better reflect the likelihood that electrolyzer systems will continue to scale in the coming years.

Other considerations: The above analysis assumes behind-the-meter power supply only. However, there is an opportunity to drive electricity cost optimization enabled by the ERCOT market structure, which does not currently have a forward capacity market. ERCOT has a unique way of measuring peak power: The ERCOT market essentially charges for use of the electric grid based on a user's volumes during times when the grid is most strained.

While the above analysis does not account for these features of the ERCOT market, this structure could be a competitive differentiator for clean **electrolysis-based** hydrogen in Texas in three ways.

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[22] For comparison, the system size costs used in this analysis are in line with other public reports:

Green hydrogen cost reduction: Scaling up electrolysers to meet the 1.5°C climate goal, IRENA, December 2020. Retrieved from: https://irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf

The Future of Hydrogen, International Energy Agency, June 2019. Retrieved from: https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf

Lazard's Levelized Cost of Hydrogen Analysis— Version 2.0, Lazard, October 2021. Retrieved from: https://www.lazard.com/media/451922/lazards-levelized-cost-of-hydrogen-analysis-version-20-vf.pdf

- By curtailing demand during those periods when ERCOT is measuring power for grid cost allocation, electrolyzer users can significantly avoid network costs
- Using less energy for hydrogen production during high-priced hours and selling unused energy back to the ERCOT ancillary markets can further reduce costs
- Turning off electrolyzers during extremely high-priced hours can help optimize costs

While high-priced hours are not common, they can have an outsized impact on economics when they do occur, even for short durations. These events are part of ERCOT's energy-only market structure and are needed to support investment in new generation assets.

Participation in such high-priced events can be lucrative. While the cap on energy prices was recently reduced from $9,000/MWh to $5,000/MWh,[23] wholesale energy prices over $1,000/MWh have occurred during 41 hours over the past three years.[24] On the other hand, ERCOT grid connections could increase the carbon intensity of produced hydrogen since the grid is not 100% powered by renewable energy.

Pathway #2: Natural-gas-based pathways with carbon capture

Multiple technologies exist today for producing hydrogen via natural gas with carbon capture, and storage (CCS). Steam methane reforming (SMR) and autothermal reforming (ATR) currently have the highest technology-readiness levels. Both processes mix natural gas with high-temperature steam to create hydrogen and (ultimately) carbon dioxide.

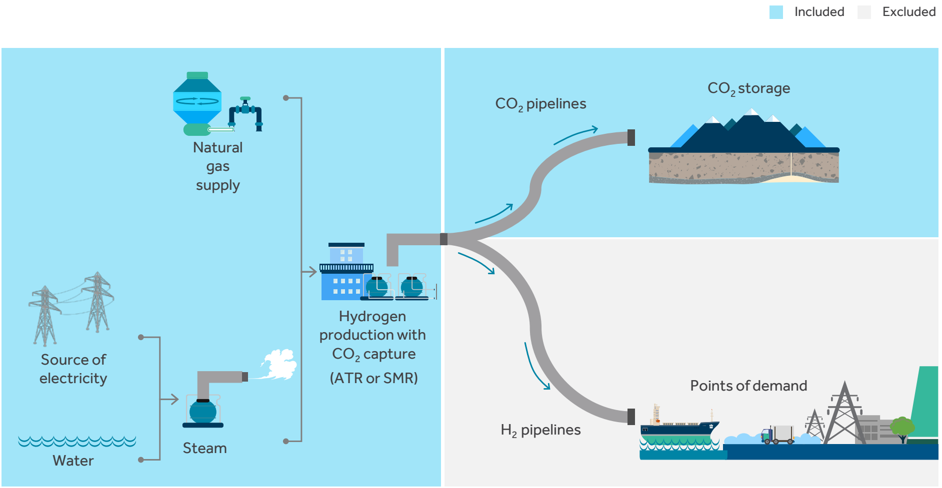
SMR is the dominant technology used today. Traditional SMR uses external heating, leading to CO_2 creation both inside the reactor (~70%) and outside the reactor (~30%). In the traditional SMR process, the CO_2 created inside the reactor is captured relatively easily, but the CO_2 outside the reactor is harder (and more expensive) to capture. Modern SMR designs are based on limiting the CO_2 creation through heat of combustion and creating a single CO_2 rich stream for efficient carbon capture. As a result, SMRs with CCS could have a CO_2 capture rate of 70-95%, depending on whether older or newer versions of the technology are being deployed.

ATR is typically somewhat less efficient than SMR. However, depending on the needs for process preheat through heat of combustion, high levels of CO_2 can be generated inside the primary reactor, providing the potential for a relatively pure stream of CO_2 for capture. ATR can lead to CO_2 capture rates of 98%. ATR will be a more suitable solution for large system sizes; SMR will tend to be adopted in size ranges below 300,000 Nm^3/h since ATR can be less efficient at these ranges. Whether retrofitting existing SMRs with carbon capture is more economical than replacing a SMR plant with a new ATR plant requires further analysis and will likely vary from plant to plant depending on capacity.

Inclusions/exclusions: Natural-gas-based hydrogen production, as modeled, has four main components: **hydrogen production, carbon capture, carbon transportation,** and **carbon storage.** For **hydrogen production**, this analysis assumes stable, low natural gas prices in Texas; ERCOT industrial electricity prices; and purification, drying, and compression of hydrogen post-production. For **carbon**

Exhibit 9

Components of modeled natural-gas-based hydrogen production



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[23] *2020 State of the Market Report for the ERCOT Electricity Markets*, Potomac Economics: Independent Market Monitor for ERCOT, May 2021. Retrieved from: https://www.potomaceconomics.com/wp-content/uploads/2021/06/2020-ERCOT-State-of-the-Market-Report.pdf

[24] This analysis excludes Winter Storm Uri (February 2021).

capture, this analysis assumes that the producer is responsible for both capital expenditures and operating expenditures. The capex includes the plant (considering ATR as the base case), carbon capture system on site, and other capex (e.g., catalyst, balance of plant/utility, installation, and assembly). Operating expenditures include electricity costs.

For **carbon transportation and storage**, the analysis assumes that the producer is responsible only for the operating expenditures of using the pipelines, not for the capital cost of building them. These assumed expenditures are the equivalent of a transportation and storage fee. This exclusion allows the analysis to focus on production costs, thereby allowing for better apples-to-apples cost comparisons across production estimates for different years and regions.

Inputs: The below analysis assumes that the operating costs for CO_2 transportation and CO_2 storage remain constant at $6/ton and $10/ton, respectively.[25] Natural gas is assumed to cost between ~$2.5/MMBtu and ~$3/MMBtu from 2020 through 2050. This estimate is based on Henry Hub and assumptions about available North American gas supply through 2050.[26] Industrial electricity prices are assumed to average $0.07/kWh for all the years studied.[27]

The analysis examines both ATR with CCS and SMR with CCS. ATR and SMR have different advantages at different scales. For the purposes of this analysis, ATR plant capacity is assumed to be 500,000 Nm³/h with a carbon capture rate of 98% and the SMR plant capacity is assumed to be 100,000 Nm³/h with a carbon capture rate of 70%. These assumptions matter because the size of the plant, (and its corresponding efficiencies at scale), and the amount of carbon captured, (i.e., how much must be transported and stored), affect the price of each kilogram of hydrogen produced.

The carbon capture rate of 70% was chosen because this represents the conventional way for traditional SMR units to reduce the carbon intensity of hydrogen. In the future, alternative cost-efficient means may be developed to increase SMR's capture rates to approach those anticipated of ATR, thereby maintaining SMR's relevancy as a viable alternative for smaller scale blue hydrogen production.[28]

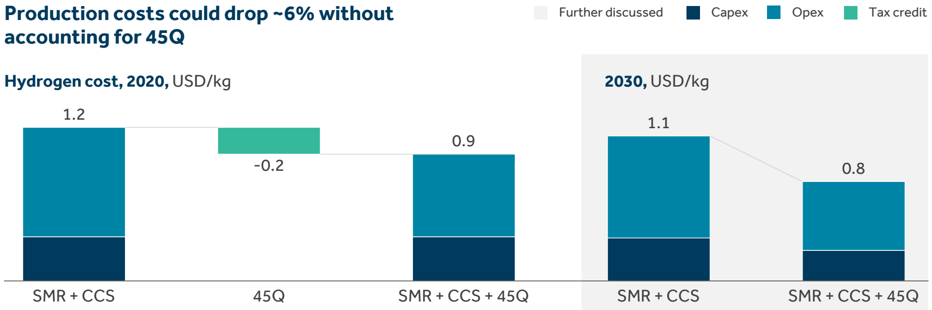
This analysis incorporates the tax credit known as 45Q as defined by the U.S. Internal Revenue Service for captured and stored CO_2, meaning the credit increases from ~$32/ton of CO_2 to $50/ton of CO_2 in 2026 and remains constant through 2038. This federal tax credit could substantially decrease the cost of natural-gas-based hydrogen production. Using these carbon capture assumptions, the model incorporates a credit for SMR with CCS of ~$0.2/kg in 2020 and ~$0.3/kg in 2030, and for ATR, the credit is ~$0.3/kg in 2020 and ~$0.4/kg in 2030.

Outputs: Based on an SMR plant capacity of 100,000 Nm³/h with a carbon capture rate of 70%, this analysis estimates the cost of hydrogen via SMR at ~$1.2/kg in 2020 and ~$1.1/kg in 2030.

Exhibit 10

Modeled cost of SMR with CCS including 45Q for 2020, 2030

Production costs could drop ~6% without accounting for 45Q



Assumptions

- Plant capacity = 100,000 Nm³/h; natural gas = ~ $2.5-3/MMBtu; greenbuild
- Carbon capture rate of 70%; unabated CO_2 emissions of ~9 kg CO_2/kg H_2
- Tax credit of ~$32/ton captured CO_2; captured CO_2 rate of ~6.5 kg CO_2 / kg H_2

- Plant capacity = 100,000 Nm³/h; natural gas = ~ $2.5-3/MMBtu; greenbuild
- Tax credit of $50/ton captured CO_2; captured CO_2 of ~6 kg CO_2 / kg H_2
- Tax credit = ~$0.3/kg H_2

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[25] These numbers are the midpoint of estimated ranges. This analysis assumes pipeline to Galveston and ~50km offshore sequestration site in the Gulf of Mexico. Assumes offshore storage location, with low end of the range assuming the reuse of wells for storage while the high end of the range assumes significant rebuild is required. Only accounts for low cost of capture (with high purity stream). Assumes 25-year lifecycle.

[26] Significant shale gas resources exist in North America with over 1500 TCF of technically recoverable resources estimated to exist below $3/MMBtu; these reserves are estimated to be sufficient to meet 20+ years of North American demand. Long-term availability of low-cost gas may be challenged, however, by midstream constraints, resulting in the sourcing of gas from more expensive basins.

[27] For context, $0.07/kWh is similar to the EIA's pricing through 2050 and does not include carbon pricing. *Annual Energy Outlook 2022*, U.S. Energy Information Administration. Retrieved from: https://www.eia.gov/outlooks/aeo/data/browser/#/?id=8-AEO2022&cases=ref2022&sourcekey=0

[28] *Techno-economic Evaluation of Deploying CCS in SMR Based Merchant H₂ Production with NG as Feedstock and Fuel*, Energy Procedia, July 2017. Retrieved from: https://www.sciencedirect.com/science/article/pii/S1876610217317277

The tax credit 45Q could reduce these costs to ~$0.9/kg and ~$0.8/kg, respectively. (See Exhibit 10).

Beyond 2030, hydrogen production costs are expected to remain relatively stable with a slight reduction to just over an estimated ~$1/kg in 2050 without tax credits. Natural gas represents the largest cost, which is estimated in this analysis to remain stable in the long run but might vary significantly in any given year.

Based on an ATR plant capacity of 500,000 Nm³/h with a carbon capture rate of 98%, this analysis estimates the cost of hydrogen via ATR with CCS at ~$1/kg in 2020 and almost the same at ~$1/kg in 2030. The 45Q tax credit could reduce these costs to ~$0.7/kg and ~$0.6/kg, respectively. Beyond 2030, hydrogen production costs are expected to remain relatively stable with costs reaching just under an estimated ~$1/kg in 2050 without tax credits. (See Exhibit 11).

From 2030 to 2050, ATR with CCS is expected to see efficiency gains in reforming natural gas and lowering emissions per kilogram of hydrogen produced. Capital expenditures might fall slightly due to technological advancements and expected future investment as ATR becomes more common.[29] Operating expenditures are expected to increase through 2050. Natural-gas-based hydrogen facilities will depend increasingly on electrification for the ATR heating process (instead of burning natural gas as a heat source).

For both the SMR and ATR pathways, this analysis assumes produced hydrogen is pressurized at 30 bar, meaning additional compression costs could be needed for pipeline transmission, trucking, or storage. This analysis does not assume any tax on carbon emissions.

Sensitivity to changes in natural gas prices

The analysis assumes that natural gas prices will remain stable at ~$2.5/MMBtu to ~$3/MMBtu for the foreseeable future based on Henry Hub, as noted above. However, predicting any energy commodity is difficult, and prices could change substantially year to year. Exhibit 12 shows the natural gas price sensitivity for hydrogen production. For 2020 and 2030, hydrogen production costs include natural gas prices ranging from $2.5/MMBtu to $4.5/MMBtu. If natural gas cost $2.5/MMBtu in 2030, for example, the analysis projects that hydrogen production could cost ~$1/kg via ATR with CCS and ~$1.1/kg via SMR with CCS. But, if natural gas cost $4.5/MMBtu in 2030, hydrogen production costs could jump to ~$1.3/kg and ~$1.5/kg, respectively. Natural-gas-based hydrogen production costs will increase as natural gas prices rise.

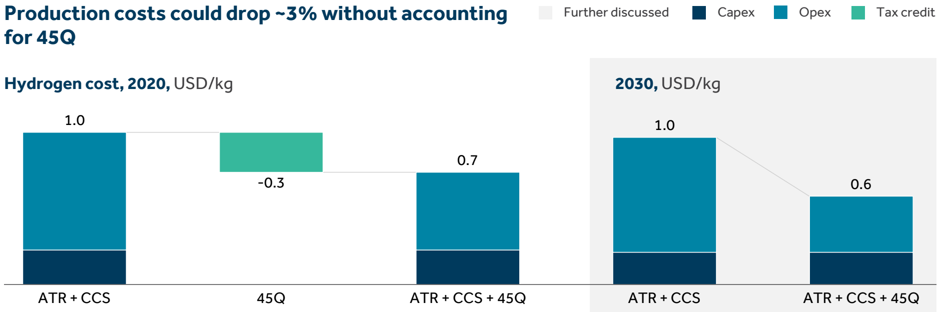
Meeting the DOE's goal of $1/kg for clean hydrogen

The above analysis illustrates how the costs of different hydrogen production pathways vary with natural gas prices. At the low end, both SMR with CCS and ATR with CCS can approach $1/kg of H_2 in 2030. But these production costs will depend on the size of the plant, the amount of carbon captured, and the natural gas price.

Exhibit 11

Modeled cost of ATR with CCS including 45Q for 2020, 2030

Production costs could drop ~3% without accounting for 45Q



Assumptions

- Plant capacity = 500,000 Nm³/h; natural gas = ~$2.5-3/MMBtu; greenbuild
- Carbon capture rate of 98%; unabated CO_2 emissions of ~8.5 kg CO_2/kg H_2
- Tax credit of ~$32/ton captured CO_2; captured CO_2 rate of ~8 kg CO_2 / kg H_2

- Plant capacity = 500,000 Nm³/h; natural gas = ~ $2.5-3/MMBtu; greenbuild
- Tax credit of $50/ton captured CO_2; captured CO_2 of ~7 kg CO_2 / kg H_2
- Tax credit = ~$0.4/kg H_2

Exhibit 12

Hydrogen production cost sensitivity to changes in natural gas prices

	2020	2030
Natural gas prices	($2.5/MMBtu - $4.5/MMBtu)	($2.5/MMBtu - $4.5/MMBtu)
ATR w/ CCS	~$1-$1.4/kg	~$1-$1.3/kg
SMR w/ CCS	~$1.2-$1.6kg	~$1.1-$1.5/kg

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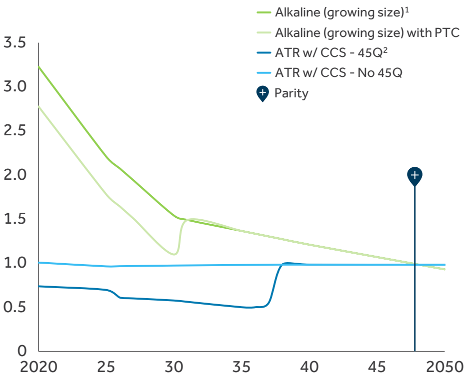
[29] Based on Hydrogen Council's analysis of anonymized data.

Exhibit 13

Direct fiscal incentives can significantly lower near-term production costs

Texas hydrogen tax credit sensitivity, $/kg

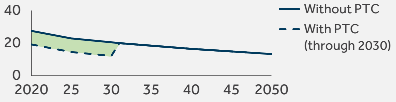


1. Growing size is defined as assuming an increase in electrolyzer system size from ~2 MW in 2020 to ~20 MW in 2025 to ~85 MW in 2030 through 2050
2. 45Q is assumed to expire in 2038

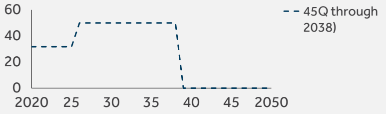
Source: McKinsey Hydrogen Insights

Assumptions

Electricity, $/MWh (LCOE expectations for onshore wind in Texas)



45Q Tax Credit, USD/ton



Conclusion

Electrolysis-based hydrogen production costs will reach parity with natural-gas-based hydrogen after 2045 even with PTC and 45Q. If either of these tax credits were extended beyond 2030 and 2038, respectively, this point of parity could change.

ATR with CCS, as modeled in this analysis, could meet the DOE's Hydrogen Shot, which seeks to reduce the cost of clean hydrogen – defined as producing no more than two kilograms of CO_2 / kilogram of produced hydrogen – to $1 per 1 kilogram in 1 decade ("1 1 1").[30] The analysis projects that the cost of hydrogen produced via ATR with CCS in Texas could reach ~$1/kg by 2030 with ~0.2 kg CO_2 / kg H_2 (measured at the point of production, as incorporated within the definition of Scope 1 emissions).[31]

The small SMR with CCS plants modeled here did not reach the DOE's targets. Its expected production cost was ~$1.1/kg with emissions of ~3 kg of CO_2 / kg of hydrogen, based on a 70% capture rate. However, improvements on SMR technology could allow the DOE's goals to be reached.

The electrolysis-based pathway discussed above will likely fall short of the DOE's targets. The cost of hydrogen produced via alkaline in Texas is projected to reach ~$1.5/kg by 2030.

Tax policies supporting both production pathways can assist in meeting DOE's clean hydrogen cost targets. For example, federal tax credits, such as the wind PTC, could help lower costs dramatically for electrolysis-based hydrogen production. Assuming that the wind PTC is extended through 2030, at-scale electrolysis-based hydrogen production costs could reach ~$1.1/kg in 2030.

For natural gas-based hydrogen production, the 45Q tax credit could substantially lower the cost of clean hydrogen. Without 45Q, the cost of ATR with CCS looks largely flat at ~$1/kg. With 45Q, the cost decreases by ~$0.3/kg in 2020 and by ~$0.4/kg in 2030.[32]

Achieving the DOE's goal of $1/kg of electrolysis-based hydrogen by 2030 would require decreasing capital expenditures by at least 20%, assuming an LCOE of $14/MWh and a wind PTC extension through 2030.[33]

Pathway #3: Emerging technologies

While electrolysis-based and natural-gas-based technologies are currently the two most common pathways for producing clean hydrogen, other pathways (e.g., methane pyrolysis, synthetic biology, and photocatalysis) could develop in the future. Emerging technologies could have a sizeable impact after 2035, provided these pathways get sufficient support and funding.

B. Cost of transport and storage

The transportation and storage of hydrogen are critical elements of the hydrogen value chain. This section examines the costs associated with such transportation and storage.

Hydrogen transport

Hydrogen transportation has two key components: the vehicle (e.g., **truck**, **pipeline**, or **ship**) and the carrier, or the form that the hydrogen will take (e.g., liquid hydrogen [LH_2], ammonia, compressed gaseous hydrogen [CGH_2],

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[30] *DOE Update on Hydrogen Shot*, U.S. Department of Energy, December 8, 2021. Retrieved from: https://www.energy.gov/sites/default/files/2021-12/h2iq-12082021.pdf

[31] The U. S. Environmental Protection Agency defines Scope 1 emissions in the following way: "Scope 1 emissions are direct greenhouse (GHG) emissions that occur from sources that are controlled or owned by an organization (e.g., emissions associated with fuel combustion in boilers, furnaces, vehicles)."

Scope 1 and Scope 2 Inventory Guidance, U.S. Environmental Protection Agency. Retrieved from: https://www.epa.gov/climateleadership/scope-1-and-scope-2-inventory-guidance

[32] **No subsidies:** ATR with CCS is $1/kg; alkaline is $1.5/kg (based on reduced cost of wind power in Texas and improved electrolyzer economics; **With subsidies (in 2030):** ATR with CCS is $0.6/kg with 45Q (no PTC for ATR); Alkaline is $1.1/kg with PTC; **Carbon intensity kg CO_2 per kg H_2 (in 2030):** ATR with CCS = 0.2 (assuming 98% carbon capture rate)

[33] McKinsey estimates.

or liquid organic hydrogen carriers[34] [LOHC]). All four carriers are currently viable low-carbon solutions.

Methanol is also a potential hydrogen carrier due to its high hydrogen content (18.75% hydrogen by weight) and its ability to remain a stable liquid at most operating temperatures, thereby allowing it to be stored and transported with minimal additional operating costs. Methanol might provide a source of low-carbon fuel for the maritime industry moving forward. This possibility warrants further study, given the Gulf Coast's existing port and petrochemical industries.

According to a 2019 DOE study,[35] methanol is more cost-effective for transporting hydrogen from the Gulf Coast to California than conventional ammonia and hydrogen. But the report did not account for the cost of producing clean hydrogen or consider the carbon intensity of each pathway. The cost and lifecycle emissions of bio-methanol and green methanol as carriers need further study.

Trucking: Trucking LH_2 or CGH_2 can be expensive but suitable for handling low or variable demand, such as at hydrogen refueling stations, or bridging the gap before constructing a pipeline. Texas has a high-density trucking market and enjoys multiple interstate highway corridors.

Pipelines: At short-to-medium distances (0-500 km), retrofitted pipelines could achieve very low transport costs, below $0.1/kg for up to 500 km of distance traveled.[36] Achieving costs in this range would depend on the availability of existing pipelines and their suitability for retrofitting as well as on transporting high volumes of hydrogen to ensure high utilization rates. Retrofitting can save 60-90% of the cost of new pipeline development.[37]

At long distances (>1,000km), onshore and undersea pipelines could transport hydrogen. The costs of pipelines can vary greatly. Based on European examples of repurposed existing infrastructure,[38] capex costs for onshore transmission networks, including compression, would range from $0.6 million/km to $1.2 million/km for retrofit and from $2.2 million/km to $4.5 million/km for new build, resulting in a range of hydrogen transport costs of ~$0.10-0.25/kg for each 1,000km.[39] Undersea transmission pipeline costs would be 1.3-2.3 times higher, given the challenges of undersea construction and operation for both the retrofit and new build options.

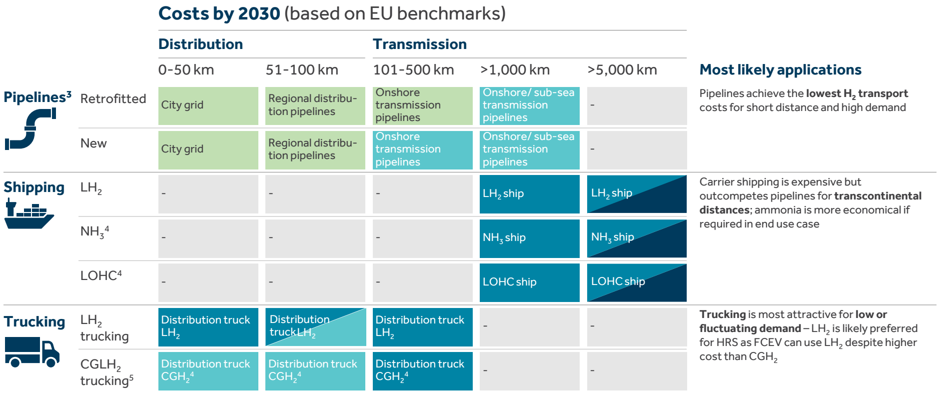
Distribution pipelines could become relevant when hydrogen demand in buildings exceeds the natural gas blending threshold. These distribution pipelines would cost much less on a

Exhibit 14

Transport option choice depends on use case, terrain, and distance and could be a meaningful portion of delivered cost

Overview of major hydrogen transport options[1]

🟩 <0.1 USD/kg
▨ 0.1-1 USD/kg
🟦 1-2 USD/kg
■ >2 USD/kg



Costs by 2030 (based on EU benchmarks)

		Distribution		**Transmission**			
		0-50 km	51-100 km	101-500 km	>1,000 km	>5,000 km	**Most likely applications**
Pipelines[3]	Retrofitted	City grid	Regional distribution pipelines	Onshore transmission pipelines	Onshore/ sub-sea transmission pipelines	-	Pipelines achieve the **lowest H_2 transport** costs for short distance and high demand
	New	City grid	Regional distribution pipelines	Onshore transmission pipelines	Onshore/ sub-sea transmission pipelines	-	
Shipping	LH_2	-	-	-	LH_2 ship	LH_2 ship	Carrier shipping is expensive but outcompetes pipelines for **transcontinental distances**; ammonia is more economical if required in end use case
	NH_3[4]	-	-	-	NH_3 ship	NH_3 ship	
	LOHC[4]	-	-	-	LOHC ship	LOHC ship	
Trucking	LH_2 trucking	Distribution truck LH_2	Distribution truckLH_2	Distribution truck LH_2	-	-	**Trucking** is most attractive for **low or fluctuating demand** – LH_2 is likely preferred for HRS as FCEV can use LH_2 despite higher cost than CGH_2
	$CGLH_2$ trucking[5]	Distribution truck CGH_2[4]	Distribution truck CGH_2[4]	Distribution truck CGH_2[4]	-	-	

1. Alternative distribution methods, such as shipping by rail, could also be feasible pending further research; 2. Gaseous Hydrogen, Liquid Hydrogen LH_2, Liquid Organic Hydrogen Carriers (LOHC), ammonia (NH3), Methanol, LNG/LCO_2 (dual-use vessels carrying liquefied natural gas on one trip and liquid CO_2 on the return trip) and solid hydrogen storage; 3. Assuming high utilization; 4. Including reconversion to H_2: LOHC cost dependent on benefits for last mile distribution and storage; 5. Compressed gaseous hydrogen

Source: Hydrogen Council and McKinsey 2021, European Hydrogen Backbone 2021

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[34] Various liquid organic hydrogen carrier materials are available, e.g., dibenzyltoluene (DBT) and benzyltoulene.

[35] *Outlook of Hydrogen Carriers at Different Scales, Department of Energy Hydrogen Carriers Workshop*, H_2@Scale, November 2019. Retrieved from: https://www.energy.gov/sites/prod/files/2020/03/f72/fcto-hydrogen-carriers-workshop-2019-anl.pdf.

Assumes 50 tpd of hydrogen demand. Assumes the hydrogen is transported once every 10 days by train to California storage terminal from the Gulf Coast (3,250 km) and then transported locally by truck (150 km) to the city gate. Assumes methanol created by one-step ATR plane (10,000 tpd)

[36] *Hydrogen Insights Report 2021*, Hydrogen Council, McKinsey & Company, July 2021. Retrieved from: https://hydrogencouncil.com/en/hydrogen-insights-2021/

[37] *Hydrogen Insights Report 2021*, Hydrogen Council, McKinsey & Company, July 2021. Retrieved from: https://hydrogencouncil.com/en/hydrogen-insights-2021/. The option to retrofit depends on the existing pipeline (material, age, location), operating conditions, and availability, which might be limited due to the long-term natural gas transmission agreements.

[38] *European Hydrogen Backbone*, Enagás, Energinet, Fluxys Belgium, Gasunie, GRTgaz, NET4GAS, OGE, ONTRAS, Snam, Swedegas, Teréga, July 2020. Retrieved from: https://gasforclimate2050.eu/wp-content/uploads/2020/07/2020_European-Hydrogen-Backbone_Report.pdf

[39] This range includes a mix of retrofit and newbuild.

per kilometer basis than transmission pipelines, considering the lower pressure and smaller size involved.

Shipping: Hydrogen shipping could be competitive with pipelines for distances >1,000km, and they are more suitable for transcontinental distances (>5,000km). LH_2, LOHC, and ammonia are the carriers with the most traction. By 2030, carrier shipping costs could cost $2-3/kg, assuming at-scale infrastructure for production and shipping.[40]

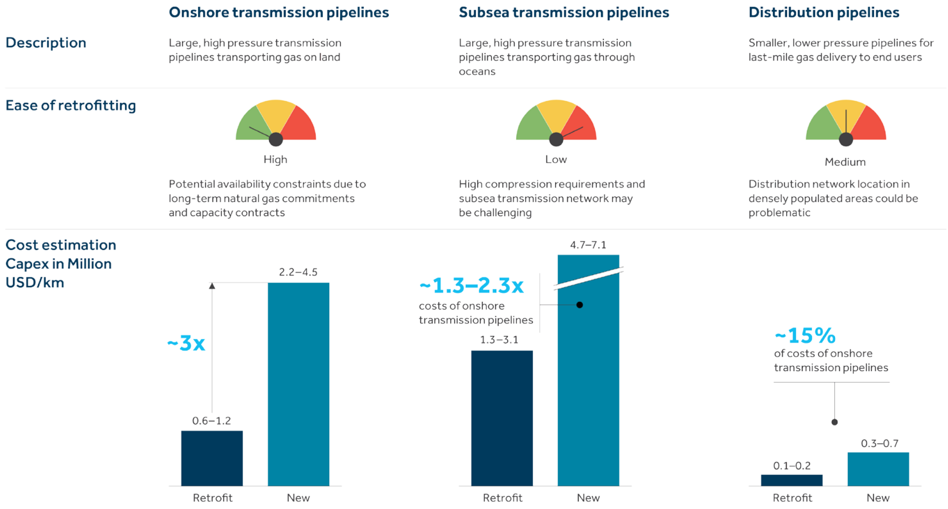
Both pipelines and shipping have advantages and disadvantages. **The optimal choice depends on use-case needs, transportation requirements after landing at port, and storage time.**

Establishing an advantage in marine shipping costs might be challenging since importing locations determine the costs at port: Costs for processes such as cracking and purification (for ammonia) or dehydrogenation[41] (for LOHC), depend on the importing countries' electricity costs, which could be high, and the availability of large-scale plants near port.

Hydrogen liquefaction: Since liquefaction increases hydrogen's storage density, liquid hydrogen could meet the growing demand for low-carbon hydrogen in mobility (such as heavy duty trucks and fuel cell locomotives) and as a storage solution in several different ways. First, distributing liquid by truck, today's predominant distribution mode, provides between 10-12 times more storage capacity compared to tube trailers at various pressures. Moving hydrogen via rail in 30,000-gallon rail cars in the future will require liquid

Exhibit 15

Comparing hydrogen pipeline production costs



	Onshore transmission pipelines	Subsea transmission pipelines	Distribution pipelines
Description	Large, high pressure transmission pipelines transporting gas on land	Large, high pressure transmission pipelines transporting gas through oceans	Smaller, lower pressure pipelines for last-mile gas delivery to end users
Ease of retrofitting	High Potential availability constraints due to long-term natural gas commitments and capacity contracts	Low High compression requirements and subsea transmission network may be challenging	Medium Distribution network location in densely populated areas could be problematic

Source: Hydrogen Council

Exhibit 16

Comparing advantages and disadvantages of LH_2, ammonia, LOHC

	LH_2	Ammonia	LOHC
Advantages / suitable applications	Liquid or high-purity H_2 is required Dehydrogenation/ cracking to convert to gaseous H_2 is not required, saving costs and increasing purity	End users need ammonia (e.g., fertilizer, marine fuel, co-firing or ammonia for power generation) High volumetric density Commercially available ammonia ships	Existing diesel infrastructure is usable for non-flammable and non-toxic materials Ability to use cheaper storage tanks Storage for long periods without loss
Disadvantages	Boil-off losses in storage and transport	High cost of cracking back to H_2 Purification necessary for high-purity applications Handling and storing restrictions due to toxicity	Dehydrogenation process requires large amounts of heat Limited H_2 carrying capacity vs. LH_2 and ammonia

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[40] *Hydrogen Insights Report 2021*, Hydrogen Council, McKinsey & Company, July 2021. Retrieved from: https://hydrogencouncil.com/en/hydrogen-insights-2021/

[41] Dibenzyltoluene (DBT) as a hydrogen carrier can be used to extract hydrogen at 99% purity.

hydrogen. Second, on-board liquid hydrogen storage provides sufficient density to allow for long-distance trucking without refueling (1000+ miles) and for fuel cell locomotives. Finally, at hydrogen refueling stations, liquid storage could replace high-pressure gaseous storage since more molecules can be compressed and since liquid hydrogen pumps consume less electricity. In addition, hydrogen liquefiers, liquid hydrogen storage tanks, and heat exchangers for hydrogen liquefaction units can be made in the United States.

Hydrogen Storage

Selecting a storage option should take into account volume, duration, the required speed of discharge, and the availability of **geological** options. Texas has both geological and **engineered** options.

Geological storage would be the best option for large-scale, long-term hydrogen storage that could bridge seasonal changes in electricity supply or provide system resilience. Salt caverns, depleted oil and gas reservoirs, and water aquifers are three options that warrant consideration.

Salt caverns are a mature option, with a Technology Readiness Level (TRL) of nine out of ten in 2021. They offer significant economies of scale, low operational and land costs, high efficiency (~98%),[42] and low contamination, as well as high discharge rates enabled by high injectivity and productivity.

Texas has salt cavern capacity and expertise. Three out of the four currently operational sites worldwide are in Texas, with total capacity of 485 GWh[43] (over 14,500 MT). **The local cost of cavern storage could be as low as $0.2/kg of hydrogen.**[44]

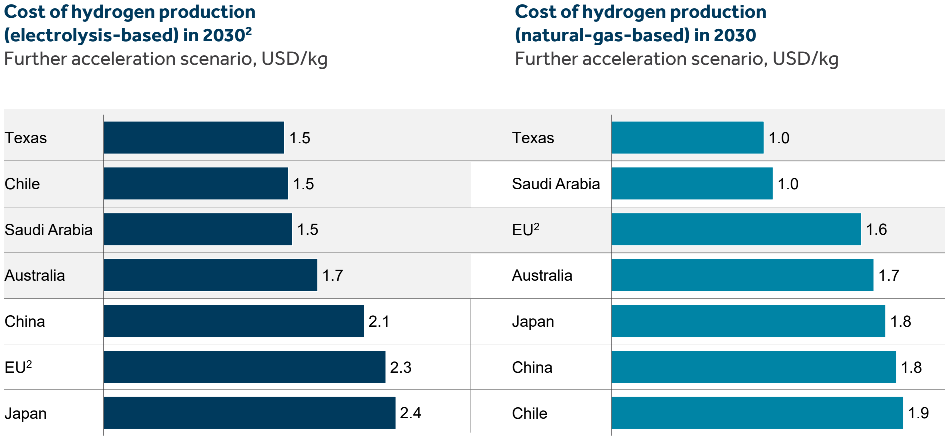
Hydrogen storage in depleted oil and gas reservoirs and aquifers is less mature, with a TRL of two in 2021. Depleted reservoirs are typically larger than salt caverns and offer high storage capacity but need to be proven feasible for hydrogen storage. Texas has abundant capacity of depleted oil and gas reservoir storage, which could be good candidates for long-term cycling if their ability as hydrogen storage units is proven feasible. Saline aquifers require additional site-specific characterization work to determine feasibility.

Microorganisms, fluids, and rocks may react with hydrogen and trigger losses or contamination. For further use in FCEVs and other high-purity applications, hydrogen stored in salt caverns, depleted fields, or saline aquifers would likely require additional processing.

Engineered storage tanks are best for small-scale applications and short-to-medium time frames, including hourly storage for hydrogen refueling stations and days or weeks for industrial applications to protect against short-term mismatches in demand and supply. Tanks typically store CGH$_2$ or LH$_2$ with high discharge rates and enjoy efficiencies of ~99%.[45]

Exhibit 17

Texas production costs in 2030 could be cost competitive in both electrolysis- and natural-gas-based hydrogen[1]



1. Further Acceleration Scenario refers to a scenario where global hydrogen demand reaches 540 MTPA in 2050. This scenario is described in more detail in Section 3.1
2. Electricity costs based on solar in Australia, Chile, KSA, wind in Texas, China, Japan, and EU; 2. Germany example

Source: McKinsey Hydrogen Insights

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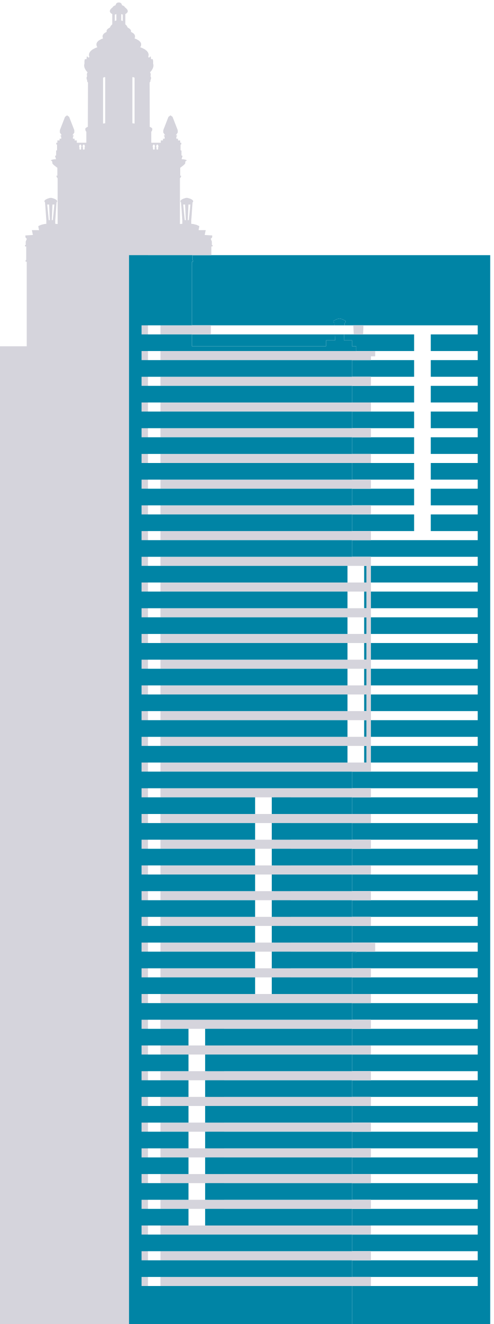
[42] Defined as quantity of hydrogen injected divided by the quantity available for extraction.

[43] *Global Hydrogen Review 2021*, IEA, October 2021. Retrieved from: https://www.iea.org/reports/global-hydrogen-review-2021.

[44] Assumes storing at 44-176 bar in 3 * $300 m^3$ caverns, 6 cycles per year.

[45] Liquefaction plants assume that the boil off from the storage tanks is captured and used again in the process.



4. Texas' export competitiveness

Local production costs are one of the most significant factors in exporting clean hydrogen: These costs vary considerably across geographies and technologies with electricity and natural gas representing the largest cost inputs for the two pathways modeled here. The analysis puts Texas' electrolysis-based hydrogen production cost in 2030 at ~$1.5/kg in the base case, but this cost could increase up to $1.9/kg (as discussed in section 2.3.A). This range could be competitive with Chile and Saudi Arabia; Texas' modeled natural-gas-based hydrogen production cost in 2030 is ~$1/kg but could increase up to $1.3/kg for ATR with CCS if natural gas prices were to rise (see Exhibit 12). This range could be competitive with other countries' natural-gas-based hydrogen exports.

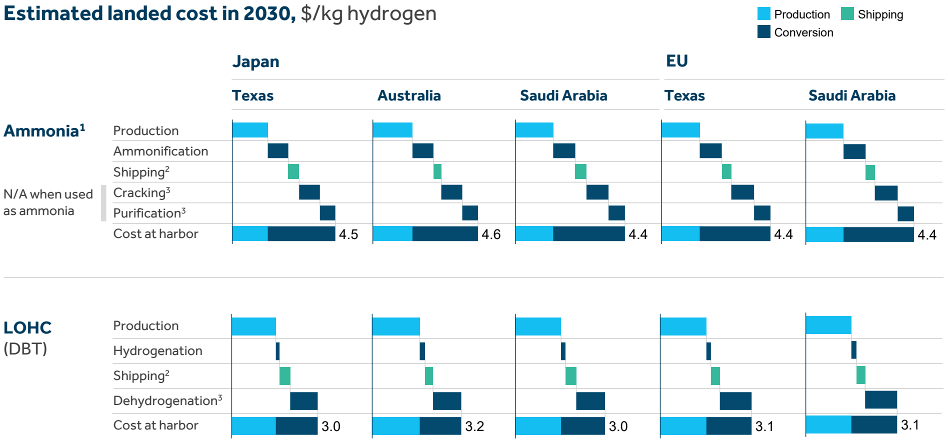
The production costs above are representative of an alkaline electrolyzer system size of ~85 MW size. Differences in capex and other opex reflect different annual production outputs as each system assumes a dedicated behind-the-meter renewable energy system, which is in turn affected by the renewable energy resources available in each region.

Transportation costs are also a significant consideration in export: While Australia and Saudi Arabia are geographicaly closer to likely hydrogen demand centers such as Japan and the European Union, respectively, Texas could potentially compete on landed cost. The estimated cost at harbor for electrolysis-based hydrogen transported to Europe or Japan, as ammonia or LOHC, is similar for Texas, Australia, and Saudi Arabia. The following ammonification costs are in line with existing green ammonia

Exhibit 18

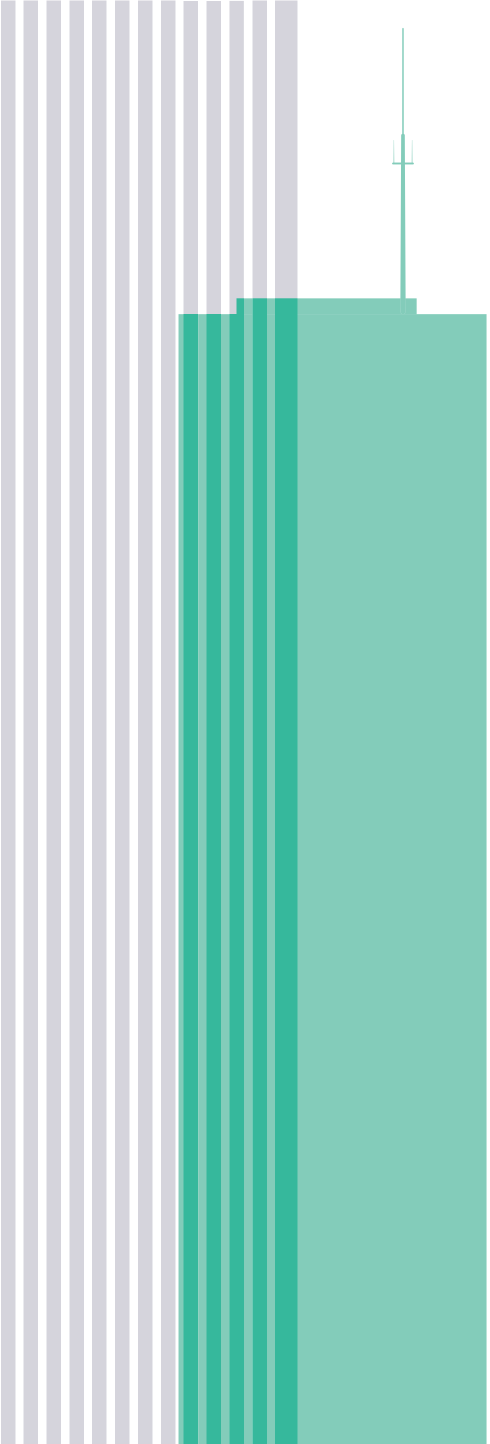
Delivered cost of hydrogen can be competitive between Texas and Australia / Saudi Arabia despite their proximity to destination

Estimated landed cost in 2030, $/kg hydrogen



1. For applications where ammonia can be used directly (e.g., marine fuel, coal blending), ammonia is a lower delivered cost than LOHC; 2. Unlike LH_2, ammonia and LOHC shipping costs are less sensitive to distance because they incur lower hydrogen losses. Import and export fees are a significant portion of shipping costs not correlated to distance whereas ship rental, fuel (assuming global HFO averages), and labor costs are correlated with distance; 3. Conversion process costs after landing are determined by hydrogen loss costs and importing country's fuel and electricity costs

Source: McKinsey Hydrogen Insights; note totals may not match with sum of subtotals due to rounding



production costs from the International Energy Agency (IEA) and the DOE when accounting for similarly scaled projects.[46]

Three main factors explain Texas' cost competitiveness on marine transport:

- Shipping costs for ammonia and LOHC are not very sensitive to distance (boil-off makes liquid hydrogen shipping costs more sensitive to distance).[47]
- The value of hydrogen losses in both processing and shipping depends on production costs in the exporting country; costs in Texas are relatively low.
- The cost for end-of-journey processing (e.g., ammonia cracking and purification and LOHC dehydrogenation) that takes place in the importing country accounts for a large portion of transport costs and is not necessarily affected by the exporting country.[48]

This export analysis does not include the costs of transport or intermediate storage when moving electrolysis-based hydrogen from West Texas to demand centers along the Gulf Coast. However, most conversion sites and facilities (e.g., liquefaction, ammonia, and truck centers) incorporate storage or will draw multiple sources for use at scale.

Beyond production and transport cost advantages, several **non-cost strategic considerations** could make Texas an attractive choice for export. These include geopolitical and national security considerations (e.g., Europe's efforts to diversify its sources of natural gas imports and accelerate hydrogen uptake); the potential for cost optimization (e.g., taking advantage of natural gas price fluctuations in different regions); the speed of capital deployment and capacity build (e.g., Texas might achieve scale earlier than Saudi Arabia and Australia); stability through diversification and more predictable sources; and long-term offtake agreements that create a potential vehicle for trade collaboration.

In many ways, the market for hydrogen exports could resemble the evolution of the liquified natural gas (LNG) market. Similar to LNG, supply-based hydrogen hubs such as in the Middle East, Australia, and North America could compete to serve demand in East Asia (e.g., Japan and South Korea). Given the cost assumptions, Texas is likely to leverage its cost and strategic advantages to export hydrogen and its derivative products.

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[46] *Outlook of Hydrogen Carriers at Different Scales, Department of Energy Hydrogen Carriers Workshop*, H2@Scale, November 2019. Retrieved from: https://www.energy.gov/sites/prod/files/2020/03/f72/fcto-hydrogen-carriers-workshop-2019-anl.pdf.

The Future of Hydrogen, International Energy Agency, June 2019. Retrieved from: https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf.

[47] These costs could be reduced in the future by using boil off to power vessels.

[48] Besides differences caused by hydrogen losses (see second bullet point).

3 Demand

This chapter highlights expected **global hydrogen demand** and hydrogen demand in Texas across a variety of applications, including **industrial, mobility, power and heat,** and **exports**. This chapter assesses whether Texas' supply advantages can potentially be paired with corresponding demand signals. These applications were selected for their relevance to the region and for their potential growth through 2050.

1. Global demand

The world is racing to cut emissions. More than 130 countries have set, or are considering, a target of net-zero emissions by 2050 to limit global warming to 1.5°C.[1] Clean hydrogen offers a long-term, scalable option for decarbonization in hard-to-abate sectors, complementing renewable power, biofuels, and energy efficiency improvements. **With an estimated abatement potential of 7 GT of CO_2 in 2050, hydrogen could contribute 20% of the total global abatement needed in 2050.**[2]

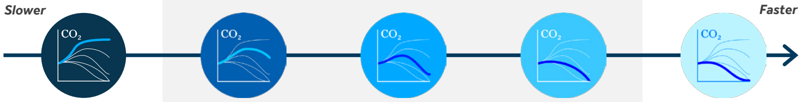
Global demand for hydrogen is expected to grow at an average rate of 4-6% per year between 2020-30, accelerating to 6-8% per year between 2030-50: Hydrogen demand could reach 540 MTPA in 2050 in the Further Acceleration scenario (see below). With more aggressive regulatory requirements and policy support, hydrogen demand could reach ~660 MTPA in 2050.[3] The overall market, including related technologies such as electrolysis and fuel cell equipment, could top $2.5 trillion by 2050.[4]

Demand signals are core to creating demand use cases based on a specific industry need. Each demand signal, in turn, should spur the creation of a value chain that involves the supply of hydrogen and/or its derivate end products (e.g., ammonia and green steel). In fact, in some sectors (e.g., commercial aviation) the demand signal for low-carbon products vastly outstrips the current supply.

Exhibit 19

A range of scenarios were considered for global demand

Speed of energy transition



Scenario description	**Fading momentum** Fading momentum in cost reductions, climate policies and public sentiment will lead to prolonged dominance of fossil fuels	**Current trajectory** Current trajectory of renewables cost decline continues, however currently active policies remain insufficient to close gap to ambition	**Further acceleration** Further acceleration of transition driven by country-specific commitments, though financial and technological restraints remain	**Achieved commitments** Net-zero commitments[2] achieved by leading countries through purposeful policies, followers transition at slower pace	**1.5C trajectory** 1.5-degree pathway is adopted globally, driving rapid decarbonization investment and behavioral shifts
Average abatement cost / shadow CO_2 price[1] $/t$CO_2$, 2030-50	< $50	$ 60 - 150	$ 85 - 160	$ 115 - 200	$ 230 +
Hypothesis on global warming[3]	> 3.5 °C	2.5 – 3.5 °C	2.0 – 2.5°C	1.8 - 2.0°C	~1.5°C

1. Hypothesis based on industry wide surveys, benchmarking, and EU net zero outputs and based on assumption carbon price will be key policy instrument to decarbonize sectors; 2. Excluding international bunkers; 3. Warming is an indication of global rise in temperature by 2100

Source: McKinsey Global Energy Perspective, Feb 2022

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1 *For a livable climate: Net-zero commitments must be backed by credible action, the United Nations.* Retrieved from: https://www.un.org/en/climatechange/net-zero-coalition

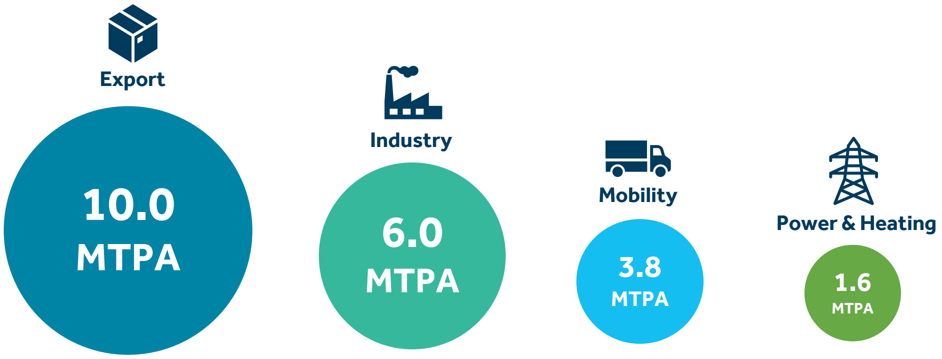
2 *Hydrogen for Net Zero: A critical cost-competitive energy vector*, Hydrogen Council, November 2021. Retrieved from: https://hydrogencouncil.com/wp-content/uploads/2021/11/Hydrogen-for-Net-Zero_Full-Report.pdf

3 *Hydrogen for Net-Zero*, Hydrogen Council McKinsey & Company, November 2021. Retrieved from: https://hydrogencouncil.com/wp-content/uploads/2021/11/Hydrogen-for-Net-Zero.pdf

4 *Hydrogen scaling up: A sustainable pathway for global energy transition*, Hydrogen Council, November 2017. Retrieved from: https://hydrogencouncil.com/wp-content/uploads/2017/11/Hydrogen-scaling-up-Hydrogen-Council.pdf

Exhibit 20

Demand for clean hydrogen could reach up to ~21 MTPA by 2050; export and industry are the largest categories



Potential to add up to **180k** jobs resulting in **$100B** contribution to local economy by 2050

Note: Numbers do not add up exactly due to rounding

While the sheer economics of a green premium might deter potential buyers, net-zero targets and commitments might increase willingness to pay premiums. For example, net-zero commitments by automakers could lead to greater willingness to pay for "green steel," enabling the steel industry to boost demand for clean hydrogen.

The hub concept provides a forum for identifying a legitimate demand signal and activating a clean hydrogen value chain (of suppliers, off-takers, and others) through catalyzing projects that can grow organically to meet increases in demand.

2. Texas' priority use cases

Production of clean hydrogen from the Texas hub catchment area (the geographic boundary used for this analysis) could reach 5 MTPA by 2035 and 11 MTPA by 2050 for meeting local demand, in addition to exporting 3 MTPA by 2035 and 10 MTPA by 2050: In 2050, Texas' production of ~21 MTPA would be the equivalent of ~4% global hydrogen demand in 2050, well above Texas' share of the global economy (~2% in 2019).[5]

In 2050, **export** (~10 MTPA of hydrogen and hydrogen-based fuels) would be the largest driver of demand, followed by **industrial applications** (~6 MTPA including feedstock and heating applications), **mobility** (~4 MTPA for ground and marine transport and aviation), and **power and heating** (~2 MTPA for utility power generation, energy storage, and natural gas blending for buildings).

Sizing methodology: This analysis estimates that Texas has an export potential of ~10 MTPA, considering a range of 8-12 MTPA based on current market share of LNG exports and assuming Texas' current percentage of global hydrogen production remains constant.[6] The hydrogen would likely be exported in the form of ammonia or other hydrogen-based carriers.[7]

A. Industrial applications

Catchment area: Hydrogen can be used in industrial applications as either a feedstock or a fuel. As a feedstock, hydrogen can be used in refining, petrochemicals, ammonia, iron, and steel. As a fuel, hydrogen can be used in high-grade heat applications in the iron, steel, cement, and chemical industries. Many organizations in these sectors have production facilities across Texas and Louisiana, and their corporate offices in the Houston area make purchasing decisions.

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[5] *2019 Texas GDP of $1.8 trillion*, U.S. Bureau of Economic Analysis, December 2021. Retrieved from: https://www.bea.gov/sites/default/files/2021-12/qgdpstate1221_1.pdf. Global GDP of $85 trillion, World Bank. Retrieved from: https://data.worldbank.org/indicator/NY.GDP.MKTP.CD

[6] This analysis takes a top-down approach in determining the export potential for hydrogen from the Texas region by averaging two different methodologies. The first methodology assumes that Texas maintains its current share of hydrogen production, (estimated at ~4% today) and maintains that share through 2050. Assuming a global demand for hydrogen of 540 MTPA in 2050, Texas would be responsible for 23 MTPA, or ~12 MTPA after accounting for local demand. The second methodology assumes that a) Texas maintains its current share of liquified natural gas (LNG) exports at around 8%, as reported by the EIA; and b) that around 20% of the estimated global 540 MTPA in 2050 is traded, as estimated by the IEA. This leads to a total MTPA from the Texas region of ~8 MTPA. Together, these methodologies lead to an estimated export potential of ~8-12 MTPA, or ~10 MTPA.

U.S. Liquefied Natural Gas Exports by Point of Exit, U.S. Energy Information Administration, March 31, 2022. Retrieved from: https://www.eia.gov/dnav/ng/ng_move_poe2_a_EPG0_ENG_Mmcf_a.htm

Global Hydrogen Review 2021, IEA, October 2021. Retrieved from: https://www.iea.org/reports/global-hydrogen-review-2021; Texas' current hydrogen production is estimated at ~3.6 MTPA with global hydrogen production estimated at ~84 MTPA

[7] *GasUnie, HES, Vopak plan ammonia, hydrogen terminal at Rotterdam*, Reuters, April 11, 2022. Retrieved from: https://www.reuters.com/article/netherlands-hydrogen/gasunie-hes-vopak-plan-ammonia-hydrogen-terminal-at-rotterdam-idUSL2N2W918W

Therefore, both Texas and Louisiana are included in the Houston catchment area for industrial hydrogen demand.

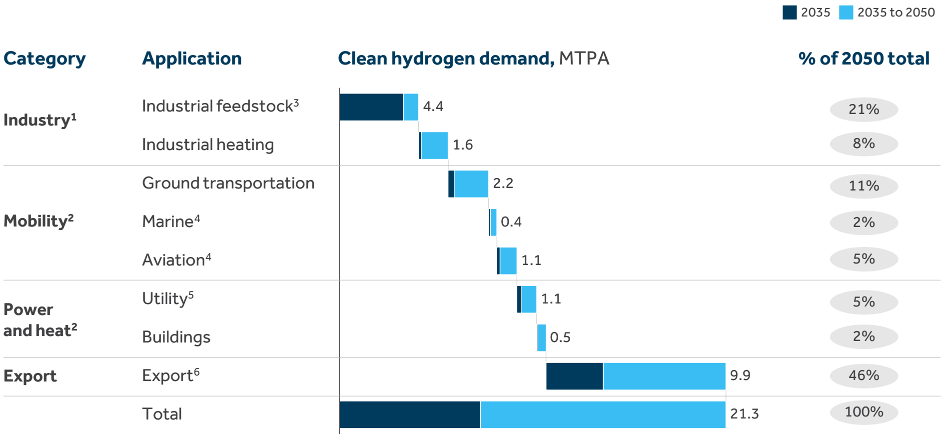
Sizing methodology: The 2050 industrial demand sizing represents the full potential for hydrogen demand assuming that all facilities in the targeted use cases in Texas and Louisiana adopt clean hydrogen, unless otherwise noted. In this analysis, facility-level GHG emissions data from the EPA's Greenhouse Gas Reporting Program (GHGRP)[8] has been translated into hydrogen demand potential by application.[9]

The 2035 demand sizing reflects how much of the full potential is achievable, by application, by then. Texas' large number of **refining**, **petrochemical**, and **ammonia** facilities could gradually adopt clean hydrogen by 2030, creating substantial hydrogen demand. However, given the relatively small number of iron and steel and cement facilities in the region, these sectors will likely not be a major demand driver over the next 15 years.

Refining: Texas refineries have the capacity to process 5.9 million barrels of crude oil per day, according to the U.S. Energy Information Administration. As of January 2020, this amounted to ~31% of total U.S. refining capacity.[10] The Houston area is home to ten refineries that collectively process more than 2.7 million barrels of crude oil per day, or ~14% of all U.S. production.[11]

Exhibit 21

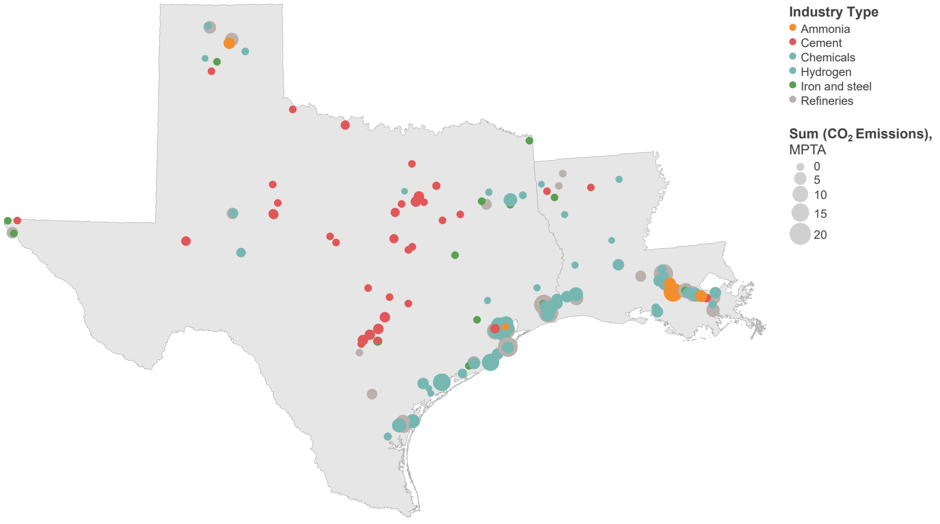
Industry and export could drive most of the demand that come online by 2035, with mobility and industrial heating to follow



1. Sizing includes Gulf Coast (Texas and Louisiana); 2. Sizing includes Texas; marine only includes Port of Houston; 3. Includes refining, petrochemicals, ammonia, iron, and steel; 4. Includes synthetic fuels and hydrogen propulsion for Texas; 5. Includes natural gas power generation and energy storage; 6. Represents hydrogen and hydrogen-based fuels (e.g., for aviation and marine) produced in Texas and consumed elsewhere.

Exhibit 22

Industrial facility CO_2 emissions in Texas and Louisiana, 2019[1]



1. Analysis uses 2019 data from the U.S. Environmental Protection Agency's FLIGHT database as well as proprietary data from McKinsey's Energy Insights emissions database

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[8] *GHGP 2019 Data Summary Spreadsheet*, EPA, August 2021. Retrieved from: https://www.epa.gov/ghgreporting/data-sets. Note where possible, 2019 data is used as the base year across applications to reduce noise from COVID-19 impact.

[9] Demand factors are 0.11t H_2 / t CO_2e for refining and petrochemicals, 0.085t H_2 / t CO_2e for ammonia manufacturing, 0.1t H_2 / t CO_2e for iron and steel production, and 0.008t H_2 / t CO_2e for cement production based on H_2 needed and CO_2e emitted per ton of product in the U.S

[10] *Texas State Energy Profile*, EIA, April 2021. Retrieved from: https://www.eia.gov/state/print.php?sid=TX

[11] *Refinery Capacity Report*, EIA, January 2020. Retrieved from: https://www.eia.gov/petroleum/refinerycapacity/archive/2020/table5.pdf

Currently, oil refineries use about two-thirds of the ten million tons of on-purpose feedstock hydrogen produced each year in the U.S.[12]

Oil refining will remain an important application of hydrogen, but as the energy transition decreases global demand for hydrocarbon liquids by 2050, the long-term need for refining capacity will decline. In the Further Acceleration scenario, the global distillation capacity of 105 million barrels per day in 2019 will drop ~27% by 2035 and ~55% by 2050.[13]

The reduction of refining capacity in North America will be uneven. The United States Gulf Coast (USGC) enjoys significant advantages in this regard: highly complex assets (producing the highest-quality yields and achieving high margins), strong operating capabilities and system efficiencies (flagship facilities, talent, and infrastructure, including the existing hydrogen network), and better access to export markets than other North American refining locations. A larger share of capacity might close in the Midwest, the West Coast, Alaska, Hawaii,[14] and Canada. Therefore, this analysis assumes 10% reduction of refining capacity in 2035 (vs. 2019), and 30% in 2050, leading to **demand for refining hydrogen of 2.0 MTPA in 2035 and 1.6 MTPA in 2050.**

Petrochemicals: Houston is responsible for more than 42% of U.S. petrochemicals capacity, according to the state of Texas.[15] This production generates an estimated ~$40 billion in revenue each year.[16] Petrochemicals are expected to remain a sizable application for clean hydrogen in 2050. The estimated total demand for **clean hydrogen in the petrochemicals sector will reach 1.5 MTPA in Texas and Louisiana by 2050**, including, but not limited to, replacement of current demand for conventionally produced hydrogen; applications in methanol, nylon, and butanol production; and substitution for natural gas as a source of heat in petrochemicals.

Ammonia: The total demand for clean hydrogen in ammonia manufacturing is expected to reach **1.2 MTPA in Texas and Louisiana by 2050**, mostly in Louisiana. Leveraging low natural gas costs, the Gulf Coast region produces a significant amount of ammonia, used primarily in fertilizer production. Natural-gas-based hydrogen production could serve this market and meet the demand for low-carbon products, at least until electrolysis-based hydrogen production costs decrease.

Ammonia could grow to meet other production requirements, including marine fuel (demand included in marine use case) and seaborne hydrogen transport (demand accounted for in other use cases).

Iron and steel: The total demand for clean hydrogen in iron and steel is expected to reach **0.2 MTPA in Texas and Louisiana by 2050**. Given that Texas already has highly advanced direct reduction plants, the state could lead the nation in the development of a low-carbon steel industry.

Direct reduction of iron (DRI) uses natural gas to produce steel with lower CO_2 emissions compared to steel production that uses blast furnaces. The DRI process can use mixtures of reformed natural gas, i.e., carbon monoxide and hydrogen, or even 100% hydrogen to make the DRI. Experts suggest a 30% mix of hydrogen with natural gas is feasible without significantly altering the production process. The higher the proportion of green hydrogen that is used, the lower the CO_2 emissions from the direct reduction process.[17]

Cement: Total demand for clean hydrogen in the cement sector is expected to **reach 0.1 MTPA in Texas and Louisiana by 2050**. Texas is home to the U.S. headquarters of CEMEX, which has already introduced hydrogen technology into the fuel mix of all its cement production facilities in Europe. CEMEX has announced plans to do the same in other facilities outside of Europe, making the company a potential user of hydrogen in the Texas region.[18]

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[12] *The Technical and Economic Potential of the H2@Scale Hydrogen Concept Within the United States*, The National Renewable Energy Lab, January 2021. Retrieved from: https://www.nrel.gov/docs/fy21osti/78956.pdf#:~:text=The%20economic%20potential%20of%20hydrogen,4.1X%20current%20annual%20consumption.&text=electrolysis%2C%20fuel%20cells%2C%20and%20hydrogen%20distribution%20technologies.

[13] *Energy Insights' Global Downstream Model*, McKinsey & Company, June 2021.

[14] Specifically the Petroleum Administration for Defense Districts 2 and 5 in the United States

[15] *Petroleum refining & Chemical products*, Texas Government, June 2015. Retrieved from: https://gov.texas.gov/uploads/files/business/petroleum-snapshot.pdf

[16] *Industry revenue of "petrochemical manufacturing" in Texas from 2012 to 2024*, Statista, September 2021. Retrieved from: https://www.statista.com/forecasts/1205390/petrochemical-manufacturing-revenue-in-texas

[17] *Comments by the Center for Houston's Future to the U.S. Department of Energy's Earthshot Request for Information,* Center for Houston's Future, July 2021. See Appendix C for hyperlink. Expert interviews were also conducted

[18] *CEMEX successfully deploys hydrogen-based ground-breaking technology*, Cemex, February 2021. Retrieved from: https://www.cemex.com/-/cemex-successfully-deploys-hydrogen-based-ground-breaking-technology

Industrial heating:[19] Total demand for clean hydrogen for industrial heating is expected to reach **1.6 MTPA in Texas and Louisiana by 2050**, with 1.1 MT in Texas and 0.5 MT in Louisiana. Hydrogen could replace fossil fuels in high-grade heat applications (above 500oC), which are used primarily by the iron, steel, plastics, and chemical industries. For low-grade heat (below 100oC) and medium-grade heat (100-500oC) applications, electrification is likely to be the preferred solution in most situations.

Hydrogen could account for up to 5% of high-grade heat applications by 2035. By 2050, hydrogen could meet 20-25% of high-grade, 5-10% of medium-grade, and up to 5% of low-grade heat and power requirements.[20] Research and development of hydrogen-compatible equipment is needed to enable further adoption.

B. Mobility

Catchment area: The primary mobility applications of hydrogen include hydrogen fuel cell trucks, light commercial vehicles (LCVs), and buses. The report considers the entire state of Texas as the catchment area for hydrogen demand in mobility since infrastructure will need to be expanded across the state to service fuel cell electric vehicles (FCEV), such as trucks along I-10, I-45, and other corridors.

Sizing methodology: To size road transportation demand for hydrogen in 2050, this analysis replaces current demand for liquid fuels by LCVs, buses, and trucks[21] with hydrogen.[22] The sizing assumes an FCEV penetration in 2050 of 12% for buses, 5% for LCVs, and 10% for heavy- and medium-duty trucks (HDTs and MDTs).[23] The 2035 road transportation demand assumes FCEV penetration of 3% for buses, 3% for LCVs, and 6% for trucks.

The demand sizing for marine transport assumes the following: that Houston's regional hydrogen use as a share of U.S. marine hydrogen demand maintains its 6.8% share of U.S. port activity.[24] Energy consumption in marine transport is expected to be fulfilled by hydrogen at 2% in 2035 and 35% in 2050.[25]

Heavy-duty trucks: Total demand for clean hydrogen in the Texas HDT sector is estimated to reach **2 MTPA by 2050**, with ~25% of that demand materializing by 2035.

Heavy-duty trucks (HDT) represent an ideal application of hydrogen for the Texas region for the following reasons:

Trucking would need limited new infrastructure to supply hydrogen as a fuel. Texas already has several high-concentration trucking markets, which would further reduce the cost of any new infrastructure.

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. Indeed, this report expects FCEVs in HDTs to break even with ICE vehicles in the U.S. by 2032, as measured by total cost of ownership per km-ton traveled.

Texas could also develop hydrogen infrastructure at the Port of Houston, replacing diesel-powered trucks in port drayage with FCEVs. Drayage trucks are usually Class 8 heavy-duty diesel trucks, which are the single largest contributor to emissions of NOx among mobile sources.

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[19] Sizing methodology assumes Texas and Louisiana's shares of total U.S. hydrogen demand from industrial heating (5MT in 2030, according to FCHEA report) are proportional to their 2019 shares of U.S. industrial energy consumption of 22% and 9%, respectively.

[20] *Road Map to a U.S. Hydrogen Economy*, FCHEA, October 2020. Retrieved from: https://www.fchea.org/us-hydrogen-study#:~:text=New%20 Report%20Offers%20Road%20Map%20to%20US%20Hydrogen%20Energy%20Leadership&text=The%20Road%20Map%20stresses%20 the,heat%20and%20feedstock%20to%20industry.

[21] *Roadway Inventory Annual Report 2019*, Texas DOT website, 2019. Retrieved from: https://www.txdot.gov/inside-txdot/division/transportation planning/roadway-inventory.html

[22] *Hydrogen Conversion Factors and Facts Card*, U.S. Department of Energy. Retrieved from: https://www.nrel.gov/docs/gen/fy08/43061.pdf. Assume around 1kg of H_2 replaces 1gallon diesel or gasoline according to US DO.

[23] *Global Energy Perspective 2021*, McKinsey & Company, January 2021. Retrieved from: https://www.mckinsey.com/industries/oil-and-gas/our-insights/global-energy-perspective-2021. Assuming Texas FCEV penetration is aligned with U.S. Adoption estimates are based on average TCO per km for ICE, BEV, and FCEV

[24] *Top 30 U.S. Ports*, Logistics Management, May 2021. Retrieved from: https://www.logisticsmgmt.com/article/top_30_u.s._ports_big_ports_got_bigger_in_2020. US port activity measured in twenty-foot equivalent units (TEUs).

[25] *Global Energy Perspective 2021*, McKinsey & Company, January 2021. Retrieved from: https://www.mckinsey.com/industries/oil-and-gas/our-insights/global-energy-perspective-2021.

According to a 2013 study, drayage trucks servicing the Port of Houston made 2.1 million gate visits, collectively emitting 325 tons of NOx emissions.[26] As of late 2021, 10,000 trucks arrived at the port every day to unload more than 280,000 containers.[27]

Port drayage projects could also benefit disadvantaged communities. A report by the Natural Resources Defense Council and the Texas Environmental Justice Advocacy Services found that pollution disproportionately affected communities near the Houston Ship Channel. Hydrogen-powered trucks could reduce these emissions.[28]

Light commercial vehicles (LCVs) and buses: Total demand for clean hydrogen in the LCV and bus sector in Texas is estimated to reach **0.3 MTPA by 2050**, with 20% of that demand materializing by 2035. The Houston area METRO has ~1,200 active buses in service today.[29] These buses can be near-term candidates for electrification. Battery electric vehicles (BEVs) and FCEVs could decarbonize city and school buses almost completely by 2035. FCEVs could capture 60% of the city bus market, which runs daily trips of ~120 miles, by 2030.[30] This report does not expect LCVs to be a major use case for hydrogen, due primarily to the popularity of BEVs. In the LCV sector, FCEVs are expected to achieve cost parity with BEVs seven to ten years after BEVs achieve cost parity with ICE vehicles. By then, a large portion of the addressable market will likely have transitioned to BEVs.[31]

Marine: This report expects total demand for clean hydrogen in the marine sector in Texas to reach 0.4 MTPA by 2050, including 0.3 MTPA for hydrogen-based fuels and 0.1 MTPA for hydrogen fuel cell ships.

Demand for hydrogen in marine transport includes hydrogen fuel cell ships and hydrogen-based fuels, i.e., ammonia and methanol. The report estimates that hydrogen-based fuels could meet 60% of U.S. marine energy needs in 2050 with hydrogen fuel cells meeting 20% of that need, up from 9% and 7%, respectively, in 2035.

Hydrogen fuel cells have limited marine applicability. While there have been demonstrations with coastal and short-distance vessels since the early 2000s, commercial operations of fuel cell vessels are nascent. The first fuel cell ferries only launched commercial operations in the U.S. and Norway in 2021.[32] In addition, the low volumetric density of hydrogen limits its direct use to short- and medium-range vessels, or those vessels with high power requirements that battery electrification cannot meet.[33]

In contrast, major industry stake-holders have announced plans to make 100% ammonia-fueled engines available as early as 2023 and plans to offer ammonia retrofit packages for existing vessels in 2025.[34] Methanol, another possibility, is more compatible with existing marine engines but has less decarbonization potential than ammonia.

Aviation: Total demand for clean hydrogen in aviation in Texas is expected to reach **1.1 MTPA in 2050**,mostly serving synfuel production rather than hydrogen propulsion.

Aviation is one of today's most carbon-intensive industries. Airplane emissions reached almost one Gt in 2019, or ~2.8% of the world's total emissions, according to the IEA.[35]

Texas is home to some of the busiest airports in the world. Almost 60 million people passed through Houston's airports in 2019.[36] Total jet fuel demand in Texas accounted for 9% of U.S. jet fuel demand in 2019.[37]

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[26] *Clean air strategy plan*, Port Houston, 2021. Retrieved from: https://porthouston.com/wp-content/uploads/CASP_Clean-Air-Strategy-Plan_2021-Update_Port-Houston_v20210122.pdf

[27] *'Truck after truck after truck': Port Houston supply chain struggling to meet demand*, Houston Chronicle, November 2021. Retrieved from: https://www.houstonchronicle.com/business/retail/article/10K-trucks-per-day-arrive-at-Port-of-Houston-as-16627026.php

[28] *Toxic Air Pollution in the Houston Ship Channel: Disparities Show Urgent Need for Environmental Justice*, NRDC, August 2021. Retrieved from: https://www.nrdc.org/resources/toxic-air-pollution-houston-ship-channel-disparities-show-urgent-need-environmental

[29] *Who we are,* METRO website, 2022. Retrieved from: https://www.ridemetro.org/pages/aboutmetro.aspx

[30] *McKinsey Energy Insights' Global Energy Perspective*, McKinsey Center for Future Mobility, February 2022.

[31] *McKinsey Energy Insights' Global Energy Perspective*, McKinsey Center for Future Mobility, February 2022.

[32] *Hydrogen-powered ferry to debut in San Francisco*, CBS News website, December 2021. Retrieved from: https://www.cbsnews.com/news/hydrogen-powered-ferry-to-debut-in-san-francisco/; LMG Marin: World's first hydrogen-powered ferry delivered to Norwegian owner Norled, Hydrogen Central, July 2021. Retrieved from: https://hydrogen-central.com/lmg-marin-first-hydrogen-powered-ferry-delivered-norwegian-owner-norled/

[33] *Global Hydrogen Demand Outlook 2021*, IEA, October 2021. Retrieved from: https://www.iea.org/reports/global-hydrogen-review-2021

[34] *Aker Clean Hydrogen and Kuehne+Nagel partner on green container shipping*, Ship Technology, February 2022. Retrieved from: https://www.ship-technology.com/news/aker-clean-hydrogen-green-shipping/

Wärtsilä launches major test programme towards carbon-free solutions with hydrogen and ammonia, Wärtsilä, July 2021. Retrieved from: https://www.wartsila.com/media/news/14-07-2021-wartsila-launches-major-test-programme-towards-carbon-free-solutions-with-hydrogen-and-ammonia-2953362

[35] *Tracking Aviation 2020. More efforts needed*, IEA, June 2020. Retrieved from: https://www.iea.org/reports/tracking-aviation-2021

[36] *Houston Airports Departs 2019 With a Record-breaking Year*, Houston Airports, February 2020. Retrieved from: https://www.fly2houston.com/newsroom/releases/houston-airports-departs-2019-record-breaking-year

[37] *Jet fuel consumption, price, and expenditure estimates, 2020*, EIA, September 2020. Retrieved from: https://www.eia.gov/state/seds/data.php?incfile=/state/seds/sep_fuel/html/fuel_jf.html

In this analysis, hydrogen demand in aviation includes demand for synthetic fuels (power-to-liquid) production and hydrogen propulsion. Demand estimates assume that synthetic fuels will meet 35% of U.S. aviation demand in 2050, and that hydrogen will meet 3% of that demand, up from 8% and 0%, respectively, in 2035.[38]

Production of synthetic fuels combines hydrogen with a carbon feedstock to create a kerosene-like fuel that current aircraft engines and fueling infrastructure can use as a drop-in fuel, meaning no major change to existing equipment is needed.[39] While less mature today, hydrogen propulsion could fuel short- and medium-range aircrafts. Hydrogen propulsion with fuel-cell systems has the potential to reduce emissions by 75-90%, followed by hydrogen turbines at 50-75%, and synfuels with direct air capture at 30-50%.[40]

In addition to airplanes, hydrogen has other airport applications, including buses, stationary power, ground support equipment, taxis, trains, and freight trucks.[41]

C. Power and heat

Catchment area: The primary power and heat applications of hydrogen include natural gas blending for **utility power generation, building heating**, and grid-scale **energy storage**. Utility-scale blending would require investment and coordination across the value chain, including upstream production, CCS, transmission infrastructure for natural-gas-based hydrogen, renewable energy infrastructure, and electrolysis investment for electrolysis-based hydrogen. Such projects would benefit from state-level policy and coordination. Therefore, this report considers the entire state of Texas the catchment area for hydrogen demand in power and heat.

Sizing methodology: To size the demand for utility power generation and building heating, the analysis uses natural gas consumption by end use in Texas,[42] assuming the same CAGR for natural gas in Texas as across the U.S.[43] The analysis assumes that blending by volume could reach 5% of natural gas demand in 2035 and 30% in 2050, with technical limitations.

Pipelines designed to deliver natural gas can likely handle blends containing up to 20% hydrogen, by volume, with only modest modifications.[44] Higher blends might require significant upgrades due in part to hydrogen's chemical properties, which can embrittle steel pipelines and create concerns about backfiring.[45]

In the following sections, the report sizes demand in three areas: utility power generation, energy storage, and buildings (both commercial and residential).

Utility power generation: Total demand for clean hydrogen in the utility power sector in Texas is expected to **reach 1.1 MTPA by 2050**.

This demand estimate assumes achieving a 30% volume blend for all Texas natural gas demand in power generation in 2050, with a 5% volume blend in 2035. This estimate aligns with efforts underway by GE and Mitsubishi Power to retrofit existing turbines to handle 30% blends of hydrogen, by volume, starting in 2025.[46] To handle high-hydrogen fuels, existing gas turbines might need to switch to a new combustion system because of hydrogen's lower energy density by volume and higher flame speed, compared with natural gas.

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[38] *Mission Possible Partnership*, McKinsey Sustainability, October 2021.Retrieved from: https://www.mckinsey.com/business-functions/sustainability/how-we-help-clients/cop26/insights

[39] *Hydrogen-powered aviation*, Fuel Cells and Hydrogen Joint Undertaking, May 2020. Retrieved from: https://www.fch.europa.eu/sites/default/files/FCH%20Docs/20200507_Hydrogen%20Powered%20Aviation%20report_FINAL%20web%20%28ID%208706035%29.pdf

[40] *Hydrogen-powered aviation: a fact-based study of hydrogen technology, economics, and climate impact by 2050*, Fuel Cells and Hydrogen 2 Joint Undertaking, July 2020. Retrieved from: https://data.europa.eu/doi/10.2843/766989; Airbus set the goal of having a commercial aircraft available by 2035 (capacity up to 200 passengers, 3,700-km range); ZeroAvia aims to have a 900-km range commercial offering in 2024

[41] *Opportunities for hydrogen in commercial aviation*, CSIRO, February 2022. Retrieved from: https://www.csiro.au/en/work-with-us/services/consultancy-strategic-advice-services/CSIRO-futures/Futures-reports/hydrogen-commercial-aviation

[42] *Natural Gas Consumption by End Use*, U.S. Energy Information Administration, February 2022. Retrieved from: https://www.eia.gov/dnav/ng/ng_cons_sum_dcu_stx_a.htm

[43] *Global Energy Perspective, 2019*, McKinsey & Company, January 2019. Retrieved from: https://www.mckinsey.com/~/media/mckinsey/industries/oil%20and%20gas/our%20insights/global%20energy%20perspective%202019/mckinsey-energy-insights-global-energy-perspective-2019_reference-case-summary.ashx

[44] *Pipeline Transportation of Hydrogen: Regulation, Research, and Policy*, Congressional Research Service, March 2021. Retrieved from: https://sgp.fas.org/crs/misc/R46700.pdf

[45] *Hydrogen embrittlement of steel pipelines during transients*, Procedia Structural Integrity, 2018. Retrieved from: https://www.sciencedirect.com/science/article/pii/S2452321618302683

[46] *Intermountain Power Agency Orders MHPS JAC Gas Turbine Technology for Renewable-Hydrogen Energy Hub*, Businesswire, March 2020. Retrieved from: https://www.businesswire.com/news/home/20200310005195/en/Intermountain-Power-Agency-Orders-MHPS-JAC-Gas-Turbine-Technology-for-Renewable-Hydrogen-Energy-Hub

Power to gas: Hydrogen for power generation, General Electric, February 2019. Retrieved from: https://www.ge.com/content/dam/gepower/global/en_US/documents/fuel-flexibility/GEA33861%20Power%20to%20Gas%20-%20Hydrogen%20for%20Power%20Generation.pdf

In the short term, prioritizing blending near existing pipelines could reduce emissions. If every Texas power plant located within three miles of an existing hydrogen pipeline blended 5% of their natural gas, by volume, with zero-carbon hydrogen, total emissions for these plants could drop 1.8 million tons per year. This reduction would be equivalent to removing almost 400,000 cars from the road. A 30% blend would be equivalent to removing 2.3 million cars from the road.[47]

Building heating: Total demand for clean hydrogen in the buildings sector in Texas is expected to reach **0.5 MTPA by 2050**.

This demand estimate assumes achieving a 30% volume blend for all Texas natural gas demand in residential and commercial buildings in 2050, with a 5% volume blend in 2035. While today's home appliances likely cannot handle natural gas blends with a high percentage of hydrogen, this could be feasible by 2050. The demand for hydrogen blending would be limited because a large percentage of Texas buildings use electricity rather than natural gas. For example, six in ten Texas homes use electricity as their primary heating source, compared with the national average of four in ten homes, according to the EIA.[48]

Energy storage: Texas could be a leader in storing excess renewable energy in the form of hydrogen due to its high generation of wind and solar power, abundant salt cavern storage options, and hydrogen pipeline network.

As renewable energy becomes more common throughout Texas, the ERCOT power region might need long-duration energy storage (LDES) in the form of hydrogen. By 2035, ERCOT forecasts that renewable energy might constitute 53% of the grid.[49] Seasonal LDES would probably be required when the grid hits 60-70% variable renewable energy, so Texas could see a significant hydrogen demand for LDES after 2035.[50]

Because the report expects most re-electrification of stored hydrogen to happen at natural gas-fired power plants,[51] the analysis includes energy storage demand in the hydrogen demand estimated for natural gas blending related to power generation.

D. Export potential

Trade could account for 20% of total demand for global hydrogen and hydrogen-based fuel in 2050, according to the IEA.[52]

Countries might import hydrogen for several reasons:

Renewable energy capacity might not be able to meet the domestic demand for both green electricity and hydrogen production. For example, Japan, Korea, central Europe, and large parts of the U.S. have limited wind and solar resources.

Local production might face high costs, likely driven by less favorable renewable generation costs or the high cost of natural gas.

Countries might have ambitious climate goals that rely on using hydrogen at a scale that exceeds their domestic production capabilities.

Japan, South Korea, and parts of Europe are likely to be net importers of hydrogen, while Australia and New Zealand, Chile, the Middle East, and North Africa are likely to be net exporters, according to the IEA. Hydrogen exporters could supply 1,800 petajoules (PJs) to Asia by 2050, under today's announced net-zero pledges.[53]

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[47] *Hydrogen Blending in Texas Natural Gas Power Plants at Scale*, The University of Texas at Austin, H2@UT, January 2021. Retrieved from: https://sites.utexas.edu/h2/files/2022/01/TX-H2-Power-Plant-Blending.pdf

[48] *Texas uses natural gas for electricity generation and home heating*, EIA, March 2021. Retrieved from:https://www.eia.gov/todayinenergy/detail.php?id=47116#

[49] *2020 Long-Term System Assessment for the ERCOT Region*, The Electric Reliability Council of Texas, December 2020. Retrieved from: https://www.ercot.com/gridinfo/planning.

[50] *Net-zero power: Long duration energy storage for a renewable grid, Long-Duration Energy Council Storage*, November 2021. Retrieved from: https://www.mckinsey.com/~/media/mckinsey/business%20functions/sustainability/our%20insights/net%20zero%20power%20long%20duration%20energy%20storage%20for%20a%20renewable%20grid/net-zero-power-long-duration-energy-storage-for-a-renewable-grid.pdf

[51] *The Technical and Economic Potential of the H2@Scale Hydrogen Concept within the United States*, NREL, October 2020. Retrieved from: https://www.nrel.gov/docs/fy21osti/77610.pdf. NGCT and NGCC power plants, as the cost of using variable renewable generation and energy storage is higher than the costs of the dispatchable generation options.

[52] *Global Hydrogen Review 2021*, IEA, October 2021. Retrieved from: https://www.iea.org/reports/global-hydrogen-review-2021.

[53] *Global Hydrogen Review 2021*, IEA, October 2021. Retrieved from: https://www.iea.org/reports/global-hydrogen-review-2021.

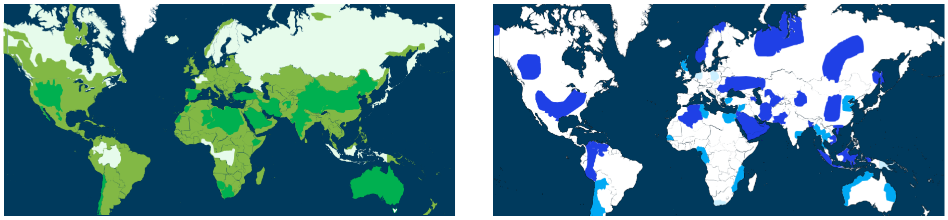
Given Texas' competitiveness in production costs, delivered costs, and other strategic considerations, the state could become a major global export hub. By 2050, Texas could export 8-12 MTPA, assuming the state maintains its current share of global hydrogen production (~4%) or future exports match Texas' current share of the global LNG export market (~8%).

Exhibit 23

Competitiveness and investment of low carbon hydrogen will be geographically driven based on resource quality

Availability and economy of resources for electrolysis-based and natural-gas-based hydrogen production

- ● Most optimal resources
- ● Less optimal resources
- ○ Least optimal resources



Wind and solar power resources for electrolysis-based hydrogen production costs

Limited resources for electrolysis-based hydrogen production in Japan, Korea, central Europe and large parts of US

Natural gas resources for natural-gas-based hydrogen production

Optimal resources for both electrolysis-based and natural-gas-based hydrogen production in the Middle East

Source: IEA, McKinsey

4 Vision and strategic roadmap

The preceding chapters examined three critical factors in building a robust regional hydrogen hub: Texas' advantages in hydrogen production and potential hydrogen demand.

This chapter outlines the vision for building and expanding the hydrogen hub in Texas. The chapter includes **guiding principles** that shape the vision, the elements of the vision, and a **strategic roadmap** to deliver on the vision, including a focus on **environmental justice.**

1. Guiding principles

Five guiding principles anchor the vision and roadmap for developing Texas into a hydrogen hub.

- **Use demand to scale supply:** Texas should fund and develop major drivers of demand to encourage market-based innovation on the supply side that could decrease costs and increase capacity. These efforts would complement Texas' current research-based innovations in hydrogen technologies. Furthermore, developing multiple, replicable projects could accelerate scaling and manage risk more effectively than pursuing a single path within each driver of supply and demand. Texas, however, should also support supply to ensure that demand signals can be effectively met.
- **Create a broad-based regional ecosystem:** Texas should create a vibrant, well-connected ecosystem that brings together diverse supply sources, demand drivers, and coordinated transport and storage infrastructure. This approach should be comprehensive and foster collaboration across public, private, and academic institutions.
- Texas should also pioneer the development of two key enablers of the hydrogen economy that look beyond physical assets – a digital layer that would support open and transparent measurement of carbon emissions and the verification needed to level the playing field for competition among diverse production pathways;[1] and a financial layer that supports trading hydrogen contracts, credits, and other instruments in a liquid market.
- **Focus on economic growth and emissions reduction:** Texas should pursue economic growth and emissions reduction as fully as possible. To scale the hydrogen economy while curbing emissions, the hub must reach and eventually exceed the DOE targets of $1/ kg of hydrogen and 2 kg CO_2/ kg of hydrogen.[2] Efforts to level the playing field for all production pathways should proceed with these ultimate goals in mind. Texas should scale and improve existing clean hydrogen technologies, while setting rigorous standards for carbon emissions, lowering the costs of new technologies, and developing the requisite infrastructure.
- **Ensure equitable and just growth:** Texas should emphasize energy and environmental justice, Diversity, Equity & Inclusion (DEI), and innovation efforts by academic, industry, and government participants in the ecosystem. In line with the Justice40 Initiative, the clean hydrogen hub should seek to reduce the energy burden on disadvantaged communities; encourage development of the domestic supply chain; and set high labor standards for hydrogen jobs. Texas should ensure an early and continuing participatory process through which impacted communities are prioritized for clean hydrogen development. The state should also ensure meaningful, robust engagement with disadvantaged communities as it develops the clean hydrogen economy.
- **Innovate at scale:** Texas should build an end-to-end innovation ecosystem that extends from basic R&D to commercialization. The state should also tap top-tier talent conducting hydrogen research at local universities and

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[1] *Open Hydrogen Initiative*, Gas Technology Institute. Retrieved from: https://www.gti.energy/ohi/#home-ohi

[2] *DOE Update on Hydrogen Shot*, U.S. Department of Energy, December 8, 2021. Retrieved from: https://www.energy.gov/sites/default/files/2021-12/h2iq-12082021.pdf

organizations to build collaborative teams across institutional lines and seek opportunities to work with researchers beyond state lines.

2. Elements of the vision

Adhering to the guiding principles, this report offers a multiphase vision for Texas to build and expand a hydrogen hub over the next 30 years. The vision and strategic priorities reflect bold aspirations for the state – stretch goals that could propel Texas toward global leadership in hydrogen across demand, supply, and enablers (including infrastructure, innovation, talent, environmental justice, and DEI) by 2050.

The right incentives could make Texas a global leader in hydrogen production, hydrogen use, innovation, and talent development by 2050. The state's total clean hydrogen production could reach 21 MT, including 11 MT to meet local demand and 10 MT to export. The hydrogen economy could create ~180,000 jobs, including direct, indirect, and induced jobs (see section 6.4 for details), and could add an estimated $100 billion to Texas' GDP, which is equivalent to 6% of Texas' 2019 GDP. The 21 MT of hydrogen production could cut global CO_2 emissions by 220 MT.

3. Strategic roadmap

This section translates that bold vision into a high-level roadmap showing how Texas could progress toward achieving that vision.

Phase 1 (2022-25): Jump-start the ecosystem

Texas could jumpstart local **demand** for clean hydrogen by substituting clean hydrogen for conventional hydrogen in industrial applications and replacing diesel trucks with FCEVs. **Supply** could be developed by retrofitting current hydrogen producing facilities with CCS equipment. Texas can also start building **infrastructure** for transport, storage, and export in the region while also developing regulatory frameworks and policy incentives.

These efforts could lead to Texas **producing** a total of ~4 MT of hydrogen (~30% higher than 2021). Texas should pursue average **production cost targets** of $2/kg for natural-gas-based hydrogen and $3/kg for electrolysis-based hydrogen by 2025.

Phase 2 (2025-2030): Scale existing use cases and explore new use cases

After establishing the hub ecosystem, Texas could increase **demand** by scaling existing use cases while exploring new ones. To increase **supply**, Texas could continue to lower production costs, scale capacity, and explore emerging technologies. Expanding **infrastructure** and conducting export pilots will further enable Texas as a hydrogen hub.

By 2030, Texas could see **local production** of ~5MT (~70% higher than 2021) and should seek average **production cost targets** of at least $1.50/kg for natural-gas-based hydrogen and $2/kg for electrolysis-based hydrogen.

Phase 3 (2030-2035): Lead the nation on hydrogen

Texas should increase **demand** for electrolysis-based hydrogen as it becomes more competitive to help lead the U.S. in hydrogen. With demand drivers fostering innovation on the **supply** side, Texas can continue to lower supply costs. Texas could also integrate **infrastructure** with other national hubs and increase export capacity.

By 2035, Texas could see **local production** of ~5 MT (~2 times 2021) with additional production of ~3 MT for export. The state should seek to hit **production cost targets** of $1 or less per kilogram for all forms of hydrogen.

Phase 4 (2035-2050): Assume global hydrogen leadership

Texas could expand **demand** by pursuing 100% clean hydrogen penetration across use cases, i.e., eliminate hydrogen produced without CCS. To strengthen **supply**, Texas could continue efforts launched in Phases 2 and 3 to decrease costs and emissions and increase capacity. Texas could finalize its export **infrastructure** for hydrogen and hydrogen-based fuels, thereby building on its national leadership to become a global leader.

By 2050, Texas could see **local production** of 11 MT, with additional surplus production of 10 MT for export. Texas should pursue further cost reduction, including on a delivered cost basis.

The following roadmaps for building demand and supply adhere to the multiphase timeline outlined above.

A. Demand roadmap

Industrial applications

Refining and petrochemicals: Hydrogen use in refining and petrochemicals offers early opportunities to leverage clean hydrogen for decarbonization, given the current scale and maturity of use cases.

New industrial applications: Texas could develop new industrial uses of hydrogen at scale. In the near term, Texas could pilot clean hydrogen use in existing natural gas applications and eventually substitute clean hydrogen for natural gas in hot briquetted iron (HBI) plants, such as the Corpus Christi

Exhibit 24

Potential demand roadmap for Texas, 2050

	Phase 1 2022 to 2025	Phase 2 2025 to 2030	Phase 3 2030 to 2035	Phase 4 2035 to 2050
Refining and petrochemicals	Pilot substituting natural-gas-based H_2 for mature conventional hydrogen	Test hydrogen as a natural gas substitute for fuel (e.g., in crackers, cogeneration)	Scale clean H_2 use for industrial feedstock and industrial heating	Clean hydrogen penetration should grow steadily to ~100%
New industrial applications	Pilot clean H_2 use in current natural gas applications	Substitute hydrogen for natural gas in HBI plants	Scale clean H_2 use in new steel & cement production	Clean H_2 penetration should reach ~100%
Ground transportation	Initiate local H_2 ground transportation network	Expand network to Texas Triangle	Enable longer-distance trucking use cases	Expand the network and access to fueling stations
Marine transportation and aviation	Pilot hydrogen-fuel-cell-powered tow tractors, FCEV forklift trucks	Explore the use of H_2-powered airport support vehicles	Commercialize airport and port support applications	Reduce costs and scale infrastructure to match demand
Power & energy storage	Conduct trials of 30-50% gas turbine blending	Test power generators that use hydrogen blends	Implement 100% H_2 or ammonia-capable turbines	Deploy H_2 grid storage & H_2, NH_3 generators at scale.
Export	Begin to build LH_2 and ammonia infrastructure	Pilot natural-gas-based hydrogen or ammonia exports to Japan and Europe	Expand natural-gas-based H_2 and ammonia exports to reach 2-4 MT total export volume	Scale domestic and international exports to reach ~10 MT in 2050

direct reduction plant of Voestalpine[3] for low-carbon steel production.

Mobility

Ground transportation: With fuel-cell vehicles maturing steadily, ground transportation demand hinges on developing a fueling network. In the near term, Texas could seek to build the largest local hydrogen ground transportation network by creating open access networks for HDTs, linking private hydrogen networks, and piloting hydrogen vehicles for public transit and anchored fleets with local operations. While compressed hydrogen will likely be the preferred fuel for heavy-duty trucks in the near term, Texas could investigate how LH_2 could help increase mileage and reduce fueling times.

This local Houston network could eventually expand to the Texas Triangle, extending into hydrogen corridors on I-10, I-45, and I-35 and potentially into California on I-10. In the long run, Texas could expand the interstate network to enable long-distance trucking use cases while also expanding the network of fueling stations.

Marine transportation and aviation: Port vessels and airport support vehicles offer some early opportunities to increase demand before hydrogen propulsion and hydrogen-fuel-supported airplanes and vessels become available. Texas could pilot hydrogen-fuel-cell-powered tow tractors as airport tugs, hydrogen-powered tugboats, and ammonia- and methanol-fueled ships at the port.

In the long run, Texas could expand the pilot of ammonia- and methanol-fueled ships. Because synthetic fuels promise to become more important in the marine and aviation energy mix after 2030, Texas should also conduct pilots in synfuel production.

Power and energy storage

In the near term, Texas could conduct trials of 30-50% gas turbine blending, distributed fuel-cell-power generation, and hydrogen to combine heat and power. Texas could test power generators that use higher-percentage hydrogen blends, including piloting 100% hydrogen- or ammonia-capable projects as some products might be available by 2025.[4] Texas could also build integrated power and hydrogen storage projects for large-scale turbines (≥200 MW).

In the long run, Texas should implement 100% hydrogen- or ammonia-capable gas turbines. Texas could also build combined hydrogen generation and power plants at scale for clean hydrogen production, co-located with zero-emission power generation, while also conducting extensive pilots of hydrogen for long-duration, seasonal, grid-scale energy storage.

Export

Hydrogen export requires scaling local supply, building the requisite infrastructure, and forming long-term export partnerships. In the near term, Texas could begin building ammonia infrastructure (e.g., ammonification) near major ports such as Houston and Corpus Christi to support marine export. Texas could pilot natural-gas-based hydrogen or ammonia exports to Japan and Europe because the absence of cracking or purification makes demand for ammonia as an end use case more cost-effective.

Building out the necessary infrastructure for ammonia exports will require further study. But ~60% of

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[3] *The HBI direct reduction process*, Voestalpine, November 2016. Retrieved from: https://www.voestalpine.com/blog/en/innovation-en/the-hbi-direct-reduction-process/

[4] *Mitsubishi Power Developing 100% Ammonia-Capable Gas Turbine*, Power Magazine, March 2021. Retrieved from: https://www.powermag.com/mitsubishi-power-developing-100-ammonia-capable-gas-turbine/

current domestic ammonia production capacity sits in Louisiana, Texas, and Oklahoma due to their access to natural gas, which is used in conventional ammonia production.[5] This accessible expertise could help Texas accelerate the development of ammonia export infrastructure.

Texas could also consider building LH_2 infrastructure around the Port of Houston. A liquefaction plant here could serve as a distribution center for LH_2 to be trucked throughout the state (and surrounding states) for smaller applications such as refueling stations and forklift operations. This approach could help meet local hydrogen demands before a wider buildout of hydrogen pipelines. An at-scale liquefaction plant could eventually be used for LH_2 exports for short distances through bulk LH_2 carriers.

Export activity is already happening in Gulf Coast ports, which are orienting themselves for potential exports of hydrogen and derivative products. For example, the Port of Corpus Christi signed a memorandum of understanding (MOU) with the Port of Rotterdam in early 2021 that outlines several shared objectives, including the development of innovative technologies such as hydrogen. Such arrangements could pave the way to create green corridors designed to connect clean hydrogen supply in the Gulf Coast with demand abroad for hydrogen products.[6]

B. Supply roadmap

Using the same multiphase timeline, this section details the strategic priorities for managing supply. Rooted in the guiding principles of reducing emissions and costs, the roadmap emphasizes scaling existing technologies and exploring emerging technologies.

Natural-gas-based capacity and industrial scale

In the near term, there may be opportunities to retrofit existing SMRs with CCS. This effort could cut emissions in certain plants where a retrofit is feasible.[7]

Texas could also expand natural-gas-based hydrogen capacity (e.g., through SMR and ATR pathways) beyond the current asset base. Furthermore, Texas could explore industrial-scale, clean hydrogen generation (e.g., through sorbent-enhanced reformers with CCS).

In the long term, Texas could explore opportunities to replace SMRs with new plant designs better suited to higher CO_2 capture rates and continue to increase production and decrease carbon intensity, especially on a lifecycle basis.

Emerging pathways

Emerging pathways offer opportunities to reduce emissions and costs. Texas can be a leader in developing and piloting new technologies. As discussed in section 6.3, Texas is home to a vibrant venture capital and start-up community, numerous top-tier universities, incubators such as Greentown Labs, and major corporations willing to dedicate resources to funding innovation.

In the near term, for example, pilots could be developed using waste-to-hydrogen, renewable-natural-gas-to-hydrogen, and other emerging technologies such as synthetic biology (e.g., Houston-based startup Cemvita Factory) and photocatalysts (e.g., Houston-based startup Syzygy Plasmonics).The Carbon Hub at Rice University in Houston has been

Exhibit 25

Potential supply roadmap for Texas, 2050

	Phase 1 **2022 to 2025**	**Phase 2** **2025 to 2030**	**Phase 3** **2030 to 2035**	**Phase 4** **2035 to 2050**
Natural-gas-based and industrial scale	Consider retrofitting SMRs with CCS & commercializing byproduct H_2	Expand natural-gas-based H_2 capacity (e.g., through SMR and ATR pathways)	Explore opportunities to replace old SMRs with plants with higher carbon capture rates	Increase production scale and decrease carbon intensity
Electrolysis-based pathways	Build capacity for high- and low-temperature electrolysis	Scale capacity and lower production costs closer to the DOE target of $1/kg	Further reduce production costs to reach and exceed the $1/kg target	Increase hydrogen production and decrease costs
Emerging pathways	Pilot waste-to-hydrogen, RNG-to-hydrogen, and other emerging technologies	Pilot offshore electrolysis & H_2 production powered by nuclear, geothermal energy	Pilot methods like woody biomass gasification and renewable liquid reforming	Continue to explore alternative pathways

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[5] *Nitrogen (Fixed) – Ammonia*, U.S. Department of the Interior, U.S. Geological Survey, January 2022. Retrieved from: https://pubs.usgs.gov/periodicals/mcs2022/mcs2022-nitrogen.pdf

[6] *Port of Corpus Christi, Port of Rotterdam Enter Into Historic Agreement*, Port of Corpus Christi, February 25, 2021. Retrieved from: https://portofcc.com/port-of-corpus-christi-port-of-rotterdam-enter-into-historic-agreement/

[7] *Resourcing Byproduct Hydrogen from Industrial Operations*, Argonne National Laboratory, May 2017. Retrieved from: https://www.energy.gov/sites/prod/files/2017/05/f34/fcto_may_2017_h2_scale_wkshp_elgowainy.pdf

developing pyrolysis technologies that transform natural gas into carbon nanotubes (i.e., solid carbon) and hydrogen. This technology has a learning curve of 30-40% per year (approximately twice as fast as solar technology).[8] Cambrian Energy operates a biomethane extraction plant in Dallas that produces the equivalent of 60,000 gallons of renewable natural gas (RNG) per day; HubZRO is already working to use this RNG to produce hydrogen.

Texas could also pilot offshore electrolysis (similar to RWE's demo project in the Dutch North Sea[9]), natural-gas-based production that uses existing pipelines at sea, or smaller-scale electrolysis-based hydrogen production powered by nuclear and geothermal energy.[10]

In the long term, Texas could pilot methods such as renewable liquid reforming (e.g., ethanol) or woody biomass gasification. Gasification projects using woody biomass as a feedstock could generate up to 70 tons of hydrogen per day and are under development in the Houston area. These projects are currently focused on higher-value liquid fuels as the end product, but hydrogen is produced during an intermediate step. If hydrogen production is incentivized, woody biomass gasification, combined with CCS, could achieve a negative carbon intensity and become an important large-volume renewable source of hydrogen in the Houston area.

4. Environmental justice

While Texas' role as the energy capital of the world has benefited the larger Gulf Coast region economically, disadvantaged communities have disproportionately shouldered the costs of industrial activities. Some disadvantaged communities,[11] composed predominantly of minorities, have suffered from the emissions of nearby industrial facilities and heavy-duty diesel trucks.

Communities along the Houston Ship Channel have experienced a host of health issues due to their proximity to industrial facilities. For example, the Harrisburg/Manchester neighborhood houses at least 30 industrial emitters of air contaminants, and 97% of residents are people of color. Bordering the shipping canal, Galena Park has over 50 industrial facilities across the wider community; 20% of residents live below the poverty line.[12] Communities around the Port of Houston have also been exposed to substantial NOx pollution from the heavy-duty trucks servicing the Port.

By becoming a hydrogen hub, Texas could address the dual challenges of revitalizing its energy economy and mitigating the impact on the communities that have suffered. Texas could take a phased approach to this effort (similar to the approach used in the supply and demand roadmaps). An environmentally just approach to creating a clean hydrogen economy could see increased life expectancy in disadvantaged communities and more economic opportunities for those communities.

Some organizations have already begun to address this issue. HETI aims to explore and understand the vision that all stakeholders have for Houston's energy transition and for enabling access to clean, reliable, resilient, and affordable energy as part of that transition. Working with a wide range of stakeholders, HETI will develop a broad, practical agenda for addressing climate equity and environmental justice issues as part of Houston's energy transition strategy. Working with experienced, science-driven, solutions-based organizations, such as the Houston Advanced Research Center (HARC) and stakeholder engagement experts, HETI is developing a framework to identify and implement energy transition strategies and actions that will address both CO_2 emissions and the equity and environmental justice issues that affect communities in the Houston region.

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[8] *Rice expert: Using carbon is key to decarbonizing economy*, Rice University website, August 5, 2021. Retrieved from: https://news.rice.edu/news/2021/rice-expert-using-carbon-key-decarbonizing-economy

[9] *North Sea green hydrogen project to harness offshore wind and use existing pipeline*, CNBC, February 2022. Retrieved from: https://www.cnbc.com/2022/02/16/green-hydrogen-demo-that-will-use-offshore-wind-planned-for-north-sea.html

[10] *Temperatures at 10 km*, SMU Geothermal Laboratory, 2011. Retrieved from: https://www.smu.edu/-/media/Site/Dedman/Academics/Programs/Geothermal-Lab/Graphics/TemperatureMaps/SMU_2011_10kmTemperature_small.png?la=en.Texas has advantages in geothermal resources along the coast as demonstrated in 10km temperatures

[11] *Interim Implementation Guidance for the Justice40 Initiative*, The White House, July 2021. Retrieved from: https://www.whitehouse.gov/wp-content/uploads/2021/07/M-21-28.pdf. The White House guidance defines disadvantaged as: 1) low income, high and/or persistent poverty; 2) high unemployment and underemployment; 3) racial and ethnic residential segregation; 4) linguistic isolation; 5) high housing cost burden and substandard housing; 6) distressed neighborhoods; 7) high transportation cost burden and/or low transportation access; 8) disproportionate environmental stress or burden and high cumulative impacts; 9) limited water and sanitation access and affordability; 10) disproportionate impacts from climate change; 11) high energy cost burden and low energy access; 12) jobs lost through the energy transition; 13) limited access to healthcare

[12] *Double Jeopardy in Houston: Acute and Chronic Chemical Exposures Pose Disproportionate Risks for Marginalized Communities*, Center for Science and Democracy, August 2016. Retrieved from: https://www.ucsusa.org/resources/double-jeopardy-houston

The HETI framework for climate equity and environmental justice will be research-based and includes several key elements:

- Community-based participatory research with disadvantaged or impacted communities to identify and develop solutions with communities from the start.
- Development of a programmatic agenda to address the specific equity and environmental justice issues identified through research, including:
  - Climate risk: climate and flood adaptation and resilience.
  - Energy burden: access and affordability.
  - Environmental hazards: quality of air and water.
  - Workforce development: access to clean energy jobs.
- Identification of key metrics to assess progress against the developed solutions.

By bringing together a wide range of organizations – corporations, communities, universities, and municipalities – HETI, with support from trusted organizations such as HARC, will work to bridge the gap between corporate climate action and environmental justice and develop solutions that can both reduce the emissions associated with climate change and improve the quality of life for all Houstonians.

Environmental justice roadmap

In phase 1, Texas could identify disadvantaged communities experiencing the greatest cumulative effects from environmental hazards. Subsequently, Texas could actively form, strengthen, and invite input from advisory panels representing such local communities, including initiatives like Houston Complete Communities to study and address the issues raised. This would require setting goals for leveraging clean hydrogen to reduce the energy burden (including adverse health and psychological outcomes) and communicating those goals to the public. Texas could implement air and water monitoring in disadvantaged communities (e.g., mobile equipment or stationary sensors) to establish a baseline and monitor progress. Texas could also prioritize launching transportation networks fueled by FCEVs for airport and port support applications as well as for school buses and public transit, which many residents of disadvantaged communities rely on.

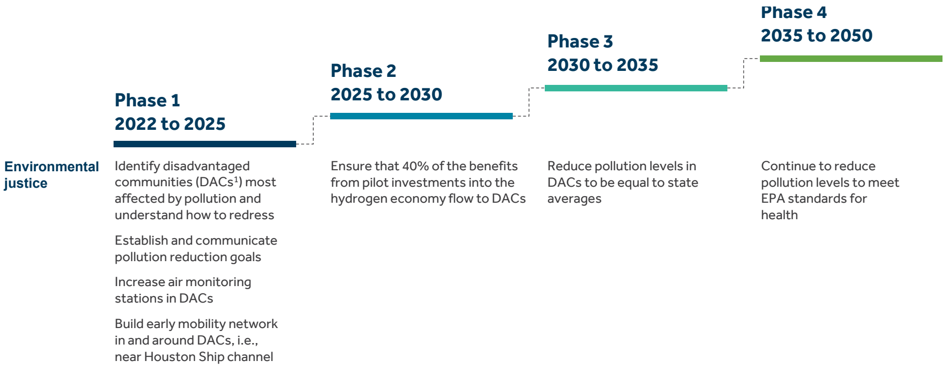
In phase 2, Texas should ensure that 40% of the benefits from pilot investments into the hydrogen economy flow to disadvantaged communities, with careful planning in land-use processes and in keeping with the Justice40 Initiative.[13]

In the process, Texas should require careful examination of the design and placement of emerging hydrogen production technologies for resiliency in inclement weather conditions (e.g., extreme temperatures) and against routine wear and tear, thereby bolstering the preparedness of disadvantaged communities against future emergencies and disasters. Through collaborations with private players and educational institutions, Texas could also prioritize providing education to disadvantaged communities, so they are empowered with unique skillsets to be more competitive in the energy transition job market. Setting requirements for minority-owned business contracts and diversity recruitment will also be critical while hydrogen infrastructure is being built.

In phase 3, Texas could continue to reduce the level of pollutants in disadvantaged communities to or below statewide averages. In phase 4, Texas could continue measuring and reducing pollution in disadvantaged communities to levels considered healthy by the EPA.

Exhibit 26

Potential environmental justice roadmap for Texas, 2050



	Phase 1 **2022 to 2025**	**Phase 2** **2025 to 2030**	**Phase 3** **2030 to 2035**	**Phase 4** **2035 to 2050**
Environmental justice	Identify disadvantaged communities (DACs[1]) most affected by pollution and understand how to redress Establish and communicate pollution reduction goals Increase air monitoring stations in DACs Build early mobility network in and around DACs, i.e., near Houston Ship channel	Ensure that 40% of the benefits from pilot investments into the hydrogen economy flow to DACs	Reduce pollution levels in DACs to be equal to state averages	Continue to reduce pollution levels to meet EPA standards for health

1. Use the White House's July 2021 "Interim Implementation Guidance for the Justice40 Initiative," which defines "disadvantaged" as: 1) low income, high and/or persistent poverty; 2) high unemployment and underemployment; 3) racial and ethnic residential segregation; 4) linguistic isolation; 5) high housing cost burden and substandard housing; 6) distressed neighborhoods; 7) high transportation cost burden and/or low transportation access; 8) disproportionate environmental stressor burden and high cumulative impacts; 9) limited water and sanitation access and affordability; 10) disproportionate impacts from climate change; 11) high energy cost burden and low energy access; 12) jobs lost through the energy transition; 13) limited access to healthcare

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[13] Suggestions in this report represent only sample interpretations of Justice40. Actual implementation should follow updated guidelines.

5 Sample projects

The hydrogen ecosystem in Texas is likely to grow in different ways. This growth will probably manifest in projects along the hydrogen value chain that fall into three broad categories: demand, infrastructure, and supply. This chapter seeks to briefly outline sample potential projects in Texas that could develop within the 2030 time frame, and their collective implication on the formation of a hydrogen hub.

Demand-based projects

1. **Large-scale new natural gas-based hydrogen production serving refining and petrochemicals operations in industrial centers such as Houston**: Refining and petrochemicals production could create significant demand signals that new natural gas-based hydrogen facilities with CCS could meet. These facilities could reduce emissions substantially in the near term and alleviate air pollution in communities near refining and petrochemical plants.
2. **Large-scale electrolysis using wind, solar, battery storage, and pipelines serving demand centers in East Texas**: Large-scale electrolysis using wind and solar in places such as West Texas could take advantage of battery storage to reduce production costs and compensate for the intermittency of renewable energy. The electrolysis involved would likely be low-temperature electrolysis such as PEM or alkaline. This project could require building pipeline infrastructure to transport hydrogen from the point of production to the point of demand, although trucks could also be used to transport LH_2 to demand centers.[1]
3. **High-temperature electrolysis co-located with demand centers in East Texas**: This project would co-locate electrolysis-based hydrogen production with demand and would use high-temperature electrolysis (e.g., SOEC). This project would demonstrate the cost-effectiveness of hydrogen production without incurring transport costs.
4. **Hydrogen blending in local natural gas grids serving local demand centers in cities around Texas**: Hydrogen blending would demonstrate the potential of using natural gas infrastructure for hydrogen to accelerate adoption and reduce capital expenditures. This project would also demonstrate the potential of decarbonizing energy-intensive buildings.
5. **Export of clean hydrogen or hydrogen-based fuels to East Asia from major ports such as Houston and Corpus Christi**: Texas enjoys substantial advantages in producing clean hydrogen and hydrogen-based fuels (e.g., ammonia and methanol), as discussed in section 2.4. This project would capitalize on Texas' attractive production economics and prepare the infrastructure needed to export clean hydrogen and hydrogen-based fuels.
6. **Clean hydrogen for hot briquetted iron (HBI) production in facilities such as those in Corpus Christi**: Texas has the largest, single-module HBI plant and therefore an opportunity to demonstrate that clean hydrogen can replace natural gas as a reducing agent and make emissions-free HBI to decarbonize steel production.

Infrastructure-based projects

7. **Port applications in drayage, material handling, distributed power generation, and marine in places such as the Port of Houston**: Switching from diesel-powered drayage trucks to hydrogen-powered trucks would immediately improve the air quality around ports, to the benefit of surrounding communities. A fueling station at a port could get supply from nearby waste-to-hydrogen production or a connection to a local hydrogen

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[1] According to one study by the University of Texas, transporting hydrogen by pipeline from West Texas would involve one-third of the cost of transmitting West Texas electricity to the point of use in Houston and producing hydrogen there. *Renewable Electrolysis in Texas: Pipelines versus Power Lines*, The University of Texas at Austin, H2@UT, August 2021. Retrieved from: https://sites.utexas.edu/h2/files/2021/08/H2-White-Paper_Hydrogen-Pipelines-versus-Power-Lines.pdf

pipeline network. This project would demonstrate the viability of an interconnected hydrogen hub in Texas. Port support vessels and vehicles for material handling could also transition to hydrogen, further reducing water and air pollution.

8. **Local fueling network built for HDTs and public transit buses around the Texas Triangle and for vehicles at airports such as George Bush Intercontinental Airport**: Building a local hydrogen fueling network for heavy-duty trucks and public transit buses would immediately reduce diesel pollution, i.e., PM and NOx. This open network would also lay the foundation for extending the fueling infrastructure for FCEV adoption at scale after 2030 to the entire state of Texas.
9. **Seasonal energy storage using geological hydrogen storage along the east and south coasts of Texas**: This project would demonstrate the feasibility of seasonal energy storage, while showcasing Texas' geological advantage. Seasonal energy storage would especially matter as more of the Texas grid becomes renewable and susceptible to intermittency.
10. **Natural gas and hydrogen dual fuel power plant / pure ammonia or hydrogen power plant such as the one in development near Bridge City, Texas**: A dual fuel power plant using natural gas and hydrogen – or gas turbines running on pure ammonia or pure hydrogen – would demonstrate the feasibility of Texas transitioning away from natural gas for power and heat.

Supply-based projects

11. **Nuclear heat source for hydrogen production using Texas' nuclear power plants**: Texas houses two nuclear power facilities. Using energy from these facilities to produce hydrogen would demonstrate the diversity of electricity sources in Texas and the feasibility of co-locating production next to a nuclear power plant.
12. **Waste-to-hydrogen pilot for hydrogen production in major cities such as Houston, Dallas, and San Antonio**: Developing hydrogen from waste would diversify Texas' production pathways, while delivering a carbon-negative fuel. Hydrogen developed from waste produces less hydrogen, making it better suited to use cases such as mobility or distributed fuel cells.

From a hub perspective, Texas could develop diverse projects across at least five emerging clusters of hydrogen value chain formation by 2030.

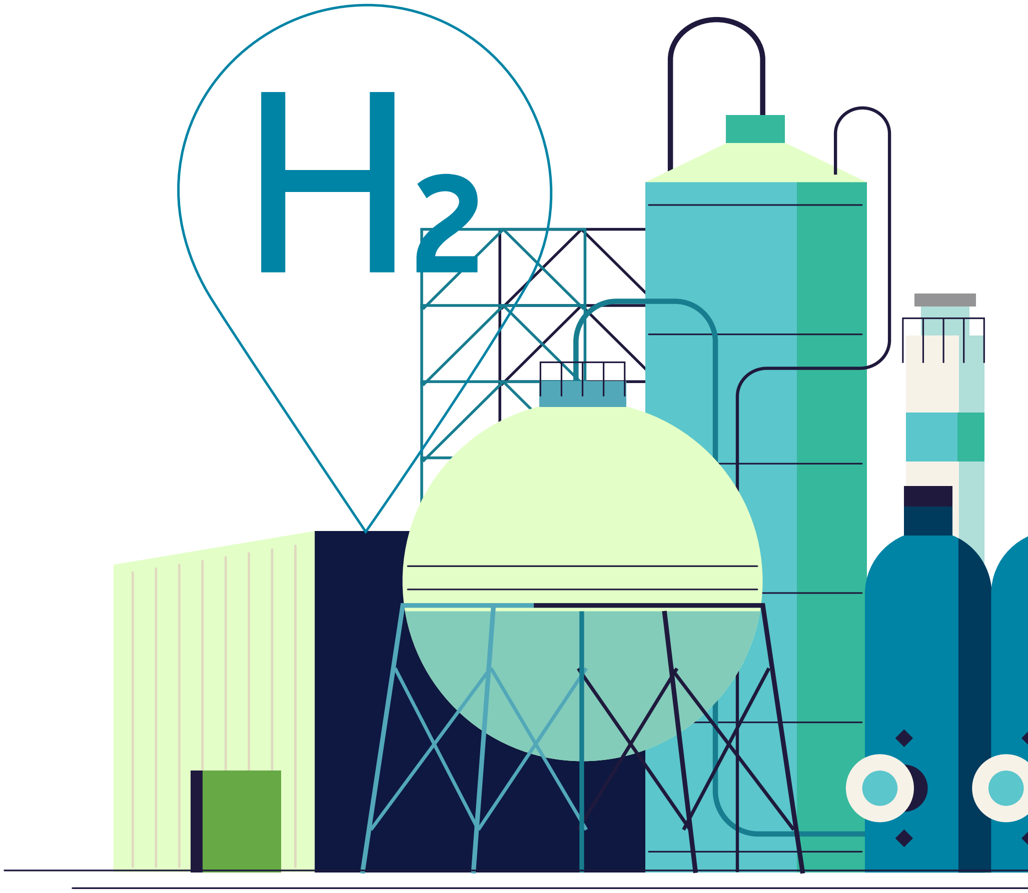
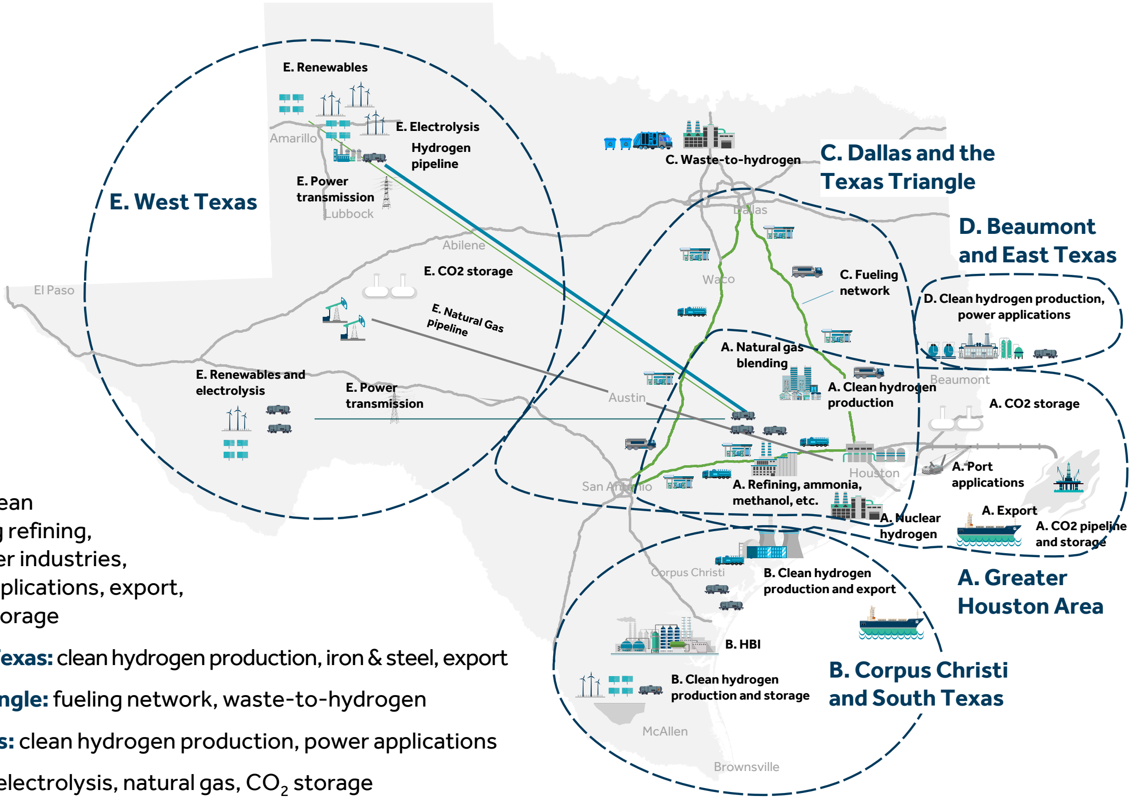


Exhibit 27

Texas hydrogen hub potential project examples by 2030

Illustrative



Emerging clusters

A. Greater Houston Area: clean hydrogen production serving refining, ammonia, methanol and other industries, natural gas blending, port applications, export, onshore and offshore CO_2 storage

B. Corpus Christi and South Texas: clean hydrogen production, iron & steel, export

C. Dallas and the Texas Triangle: fueling network, waste-to-hydrogen

D. Beaumont and East Texas: clean hydrogen production, power applications

E. West Texas: renewables, electrolysis, natural gas, CO_2 storage

As discussed below, Texas and the entire Gulf Coast region are uniquely situated to create a substantial hydrogen ecosystem because the assets extend across both Texas and Louisiana.

A. The **Greater Houston Area** could house clean hydrogen production from various pathways, serving applications in industrial feedstocks (refining, ammonia, and methanol, among others), utility grid natural gas blending, port applications, and export of hydrogen and hydrogen-based fuels. Greater Houston could also host onshore and offshore CO_2 storage supporting hydrogen production.

B. **Corpus Christi and South Texas** could house clean hydrogen production, serving applications such as iron and steel and export of hydrogen and hydrogen-based fuels.

C. **Dallas and the Texas Triangle** could house a regional hydrogen fueling network for ground transportation supplied by sources such as waste-to-hydrogen production. This network could eventually connect with nearby states, such as Louisiana.

D. **Beaumont and East Texas** could house clean hydrogen production by expanding upon existing hydrogen infrastructure, serving applications such as power generation.

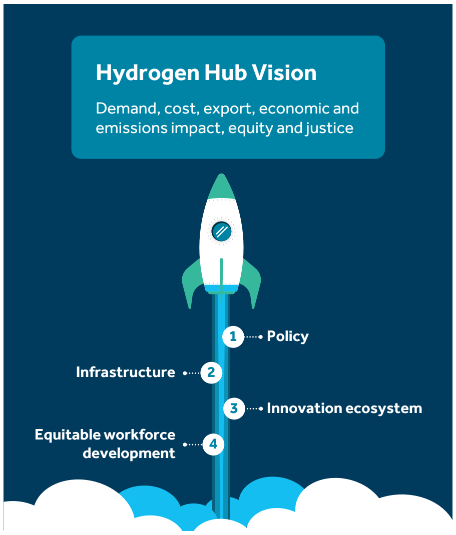
E. **West Texas** could house renewable and natural gas supplies, onshore CO_2 storage, and clean hydrogen production co-located with renewables.

6 Cross-cutting enablers

This chapter examines four cross-cutting enablers that could accelerate the development of Texas as a hydrogen hub: policy, infrastructure, innovation, and equitable workforce development.

Exhibit 28

Key enablers in creating the hydrogen hub



1. Policy

The scaling up of hydrogen is likely to face significant challenges in developing R&D support, direct financial incentives for clean hydrogen production and related sectors such as renewables and CCS, demand enablement, and regulatory frameworks. Overcoming these challenges will likely require policy interventions at the federal and state levels. This report has adopted an accelerated timeline, which could be disrupted by several factors.

First and foremost, policymakers could fail to create the needed regulatory architecture to help encourage development of a hydrogen hub. Companies are not likely to risk investing in new infrastructure or assets without an established regulatory framework (e.g., lack of detailed guidance on permitting and siting). This possibility is especially real for Texas, as the state legislature meets every other year and could conceivably be busy with other pressing legislation during the next session, thereby delaying the hydrogen hub's development by two more years.

Another potential impediment would be the inability to coordinate the supply chain around the development of new technologies or capacity related to hydrogen production and export, (e.g., required ammonia carrying vessel capacity for exports.)

Finally, a hub ecosystem will hinge upon industrial trunk line development with open access. This will require coordinated action between key players, supported by fit-for-purpose incentives which spur investments in shared infrastructure. Any failure on this front could significantly limit scaling hydrogen production in the region.

This section offers examples of promising policy approaches, both existing and potential. The policies discussed are not exhaustive; they present a sample view. **Efforts to refine, prioritize, and advocate for appropriate policies would require further study**.

1.1. Federal interventions

National commitments and targets

The U.S. Department of Energy has set a goal of $1/kg of hydrogen and an emissions goal of 2 kg of CO_2 / kg of hydrogen as part of the Hydrogen Earthshot effort.[1]

Many countries have started setting goals for reaching specified levels of hydrogen consumption. For example, Japan has set the targets of consuming 3 MTPA and producing 420 KT by 2030. Canada has set the goal of using 4 MTPA by 2030.[2]

The Department of Energy has announced multiple initiatives to fund hydrogen R&D and pilots, including $8 billion for regional clean hydrogen hubs and $500 million for clean hydrogen manufacturing and recycling initiatives.[3]

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[1] *DOE Update on Hydrogen Shot*, U.S. Department of Energy, December 8, 2021. Retrieved from: https://www.energy.gov/sites/default/files/2021-12/h2iq-12082021.pdf

[2] *Global Hydrogen Review 2021*, IEA, October 2021. Retrieved from: https://www.iea.org/reports/global-hydrogen-review-2021

[3] *Fact Fact Sheet: Biden-Harris Administration Advances Cleaner Industrial Sector to Reduce Emissions and Reinvigorate American Manufacturing*, The White House website, February 2022. Retrieved from: https://www.whitehouse.gov/briefing-room/statements-releases/2022/02/15/fact-sheet-biden-harris-administration-advances-cleaner-industrial-sector-to-reduce-emissions-and-reinvigorate-american-manufacturing/

Direct federal incentives for hydrogen production and storage

Several pending bills include policies to encourage hydrogen production and storage.

- **Build Back Better Act** (H.R. 5376), introduced into Congress in September 2021, would provide production tax credits of up to $3/kg of hydrogen for ten years after the hydrogen production facility goes into service. To qualify for the full tax credit, the produced hydrogen would have to reduce lifecycle greenhouse gas emissions by at least 95%, compared with hydrogen produced via SMR today. The tax credit would decrease on a sliding scale; the lowest possible credit would be $0.60/kg of hydrogen produced.[4]
  - **Section 136403** would create a 30% credit for qualified commercial electric vehicles and includes fuel cell electric powertrains.[5]
  - **Section 136405** would create an alternative fuel refueling property credit that would raise the current cap on the investment tax credit from $30,000 to $100,000, which would help support the building of hydrogen fueling stations.[6]
- **Clean H_2 Production Act of 2021** (S. 1807), introduced into Congress in May 2021, would grant a tax credit of up to $3/kg for producing clean hydrogen. The bill defines clean as hydrogen that reduces lifecycle greenhouse gas emissions at least 50%, compared with hydrogen produced today using SMR without CCS. The bill would also provide tax incentives for investing in clean hydrogen facilities.[7]
- **Clean Hydrogen Production and Investment Tax Credit Act of 2021** (H.R.5192), introduced into Congress in September 2021, would grant a tax credit for producing qualified clean hydrogen. The bill defines *qualified clean hydrogen* as any hydrogen production process that reduces lifecycle greenhouse gas emissions at least 40%, compared with existing hydrogen production pathways, e.g., SMR.
  The tax credit would depend on the exact percentage of emissions reduction, with a maximum credit of $3/kg of hydrogen for the ten years after the hydrogen production facility goes into service.[8] This tax credit structure is very similar to the House-passed version of the Build Back Better Act.
- **Growing Renewable Energy and Efficiency Now Act of 2021 (H.R. 848)**, introduced into Congress in February 2021, would expand a 30% investment tax credit (ITC) to "energy storage technology," including equipment for hydrogen storage, that begins construction in 2022 through 2026.[9]

Several other approaches warrant consideration.

- **Contract for Difference (CfD) approach** under consideration by the U.K. Department for Business,

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[4] *H.R.5376 – Build Back Better Act*, U.S. Congress website, September 2021. Retrieved from: https://www.congress.gov/bill/117th-congress/house-bill/5376

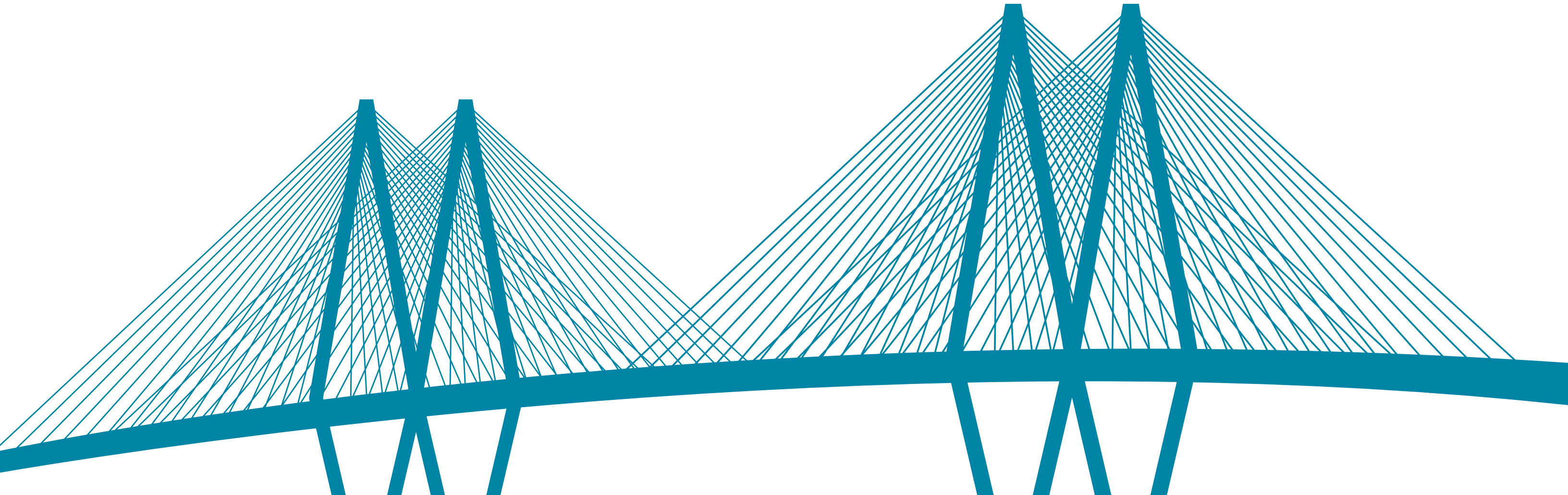
[5] *Build Back Better Act — Rules Committee Print Section-By-Section*, U.S. House Committee on Rules. Retrieved from: https://rules.house.gov/sites/democrats.rules.house.gov/files/Section_by_Section_BBB.pdf

[6] *Build Back Better Act — Rules Committee Print Section-By-Section*, U.S. House Committee on Rules. Retrieved from: https://rules.house.gov/sites/democrats.rules.house.gov/files/Section_by_Section_BBB.pdf

[7] *S.1807 – Clean H2 Production Act*, U.S. Congress website, May 2021. Retrieved from: https://www.congress.gov/bill/117th-congress/senate-bill/1807?s=1&r=5

[8] *Clean Hydrogen Production and Investment Tax Credit Act of 2021*, H.R.5192, 2021, U.S. Congress website, September 2021. Retrieved from: https://www.congress.gov/bill/117th-congress/house-bill/5192?s=1&r=28

[9] *H.R.848 - GREEN Act of 2021*, U.S. Congress website, February 2021. Retrieved from: https://www.congress.gov/bill/117th-congress/house-bill/848



Energy and Industrial Strategy (BEIS). Responsible for energy policy in the U.K., BEIS is working with industry to identify the most efficient approach to supporting hydrogen production and storage and CO_2 capture. The group is considering CfD to guarantee selling low-carbon hydrogen at prices comparable to incumbents (e.g., petrol and diesel) for the duration of the contract, potentially 15 years.[10]

- **Hydrogen investment tax credit** against the cost of hydrogen production equipment would further encourage the production of hydrogen and domestic manufacturing.

Direct federal incentives for renewable electricity production can be found in current and potential policies.

- **The Production Tax Credit** (PTC) applies to renewable electricity generation, but only to renewable energy construction started before December 31, 2021. Qualifying construction can receive 60% of the full credit amount, or about $15/MWh.[11] An extension of the PTC would further reduce the cost of electricity in electrolysis-based hydrogen, a major source of cost. A PTC valued at the full $15/MWh could have substantial impact on the levelized cost of hydrogen. The cost of hydrogen in 2025 and 2030 would drop 23% and 29%, respectively, if the PTC continued through the end of the decade.
- **The Investment Tax Credit** (ITC) for solar is set to decrease from 26% today to 10% for construction after December 31, 2023. Extending the ITC at 26% would further reduce the cost of solar energy and therefore electrolysis-based hydrogen produced with renewable energy generated by photovoltaic systems.[12]

Federal CCS incentives stimulate investment in CCS value chains.

- The federally administered tax credit per ton of captured CO_2 known as **45Q** is set to expire in January 2026, too soon for some projects in the planning phase to qualify. Supporting a 45Q extension might be a priority for Texas. In addition, 45Q does not always provide adequate commercial certainty for large-scale projects; alternatives and extensions warrant exploration.
- **Coordinated Action to Capture Harmful Emissions Act** (H.R.3538), introduced into Congress in May 2021, could address the above issues. The bill would increase the 45Q tax credit to $85/ton of CO_2 sequestered.[13]

The U.K. is considering a regulated long-term returns model for hydrogen and CO_2 pipelines, funded through the existing Regulated Asset Base (RAB) model. Other models under consideration include a public and privately owned entity, cost plus open book, waste sector type contractor, and hybrid models.[14]

Federal policies to build hydrogen demand exist today, but more are needed to encourage different end users to adopt hydrogen. Current policies include:

- **The Zero Emissions Airport Vehicle and Infrastructure Pilot Program** reimburses airports up to 50% of the cost of purchasing zero-emissions vehicles or modifying existing vehicles to handle hydrogen.[15]
- **The Port Infrastructure Development Program** provides funding through 2026 for projects that reduce or eliminate port-related emissions, including hydrogen fueling infrastructure. The Infrastructure Investment and Jobs Act of 2021 appropriated $450 million to this program for fiscal year 2022.[16]

The Department of Transportation is planning a grant program to direct funding toward alternative fuel infrastructure, including hydrogen fueling infrastructure in public areas, parks, roads, and schools. The program might offset up to 80% of project costs and would focus especially on low- and moderate-income neighborhoods.[17]

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[10] *HyNet North West*, HyNet website, 2020. Retrieved from: https://hynet.co.uk/wp-content/uploads/2020/10/HyNet_NW-Vision-Document-2020_FINAL.pdf

[11] *Production Tax Credit and Investment Tax Credit for Wind*, U.S. Department of Energy's Office of Energy Efficiency & Renewable Energy. Retrieved from: https

[12] *Guide to the Federal Investment Tax Credit for Commercial Solar Photovoltaics*, U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy. Retrieved from: https://www.energy.gov/eere/solar/homeowners-guide-federal-tax-credit-solar-photovoltaics

[13] *H.R.3538 – Coordinated Action to Capture Harmful Emissions Act*, U.S. Congress website, May 2021. Retrieved from: https://www.congress.gov/bill/117th-congress/house-bill/3538

[14] *Business Models for Carbon Capture, Usage and Storage*, Department for Business, Energy, & Industrial Strategy, September 2019. Retrieved from: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/819648/ccus-business-models-consultation.pdf

[15] *Hydrogen Laws and Incentives in Federal*, U.S. Department of Energy, Alternative Fuels Data Center. Retrieved from: https://afdc.energy.gov/fuels/laws/HY?state=US

[16] *About Port Infrastructure Development Grants*, U.S. Department of Transportation, Maritime Administration, February 2022. Retrieved from: https://www.maritime.dot.gov/PIDPgrants

[17] *Hydrogen Laws and Incentives in Federal*, U.S. Department of Energy, Alternative Fuels Data Center. Retrieved from: https://afdc.energy.gov/fuels/laws/HY?state=US

Potential regulatory frameworks warrant consideration as Texas plans efforts to build a hydrogen hub.

- **CCS:** Considerations in CCS policy and regulations include R&D support, onshore pore space access, utilization for geological storage of CO_2, and long-term ownership and liabilities.
- **Hydrogen safety and blending codes:** Building on current natural gas regulatory frameworks could simplify and accelerate efforts to create a hydrogen regulatory framework. Hydrogen is currently regulated as a "flammable gas" under the Department of Transportation's Pipeline and Hazardous Materials Safety Administration (PHMSA), which also regulates existing hydrogen infrastructure.[18] The Federal Energy Regulatory Commission regulates the interstate transmission of natural gas.

1.2. State policies

State commitments and targets

Texas could set goals for reaching certain levels of hydrogen adoption by application, such as FCEV adoption in trucking. These commitments would help to align the efforts of private and public businesses in the hydrogen economy and establish Texas as a global leader in hydrogen.

Texas could provide funding for development of a hydrogen hub in the state and partnerships with neighboring states.

Direct incentives could encourage action on several dimensions of hub building.

- **State tax incentives** could include Chapter 313 renewal (the Texas Economic Development Act), Chapter 311 (Tax Increment Reinvestment Zones), and a tax freeze or ten-year exemption for hydrogen production and consumption.
- **Development of a low-carbon fuel standard** could encourage the production of hydrogen fuel by offering a tax credit for each kilogram of hydrogen produced.
- **Renewable electricity policies** could include additional funding for transmission infrastructure, such as Competitive Renewable Energy Zones II (CREZ II).
- **State funding for CCS** and other elements of the value chain required to produce hydrogen, including production, pipeline distribution, energy storage, carbon capture and sequestration, and fueling infrastructure. This funding could also support a quality jobs program for hydrogen infrastructure development.

State policies are needed to encourage adoption of hydrogen by different end users. Potential policies include:

- **Hydrogen-specific revisions of TERP guidelines:** The Texas Emissions Reduction Plan (TERP) offers incentives to businesses to reduce vehicle emissions. Texas could revise the TERP to include incentives for businesses to switch to hydrogen for vehicles or equipment.
- **Tax credits, rebates, and/or grants for hydrogen fuel cell vehicles:** Texas could offer tax credits or deferments for the purchase of these vehicles, structured like the $7,500 federal tax credit currently available for the first 200,000 models of a BEV. A grant program could encourage private companies to switch to hydrogen fuel cell commercial trucks.
- **Renewable portfolio standards:** Texas could establish a renewable portfolio standard for hydrogen, such as directing utilities to blend a certain percentage of hydrogen into natural gas.
- **Rate base recovery:** Texas could allow utilities to recover the cost of hydrogen blending. Minnesota's Natural Gas Innovation Act shows this practice in action. The law lets utility companies petition state regulators to recover the costs of innovative projects to decarbonize operations, i.e., hydrogen blending.[19]
- **Distributed energy incentives:** California's Self-Generation Incentive Program gives rebates to customers who have installed qualifying distributed energy systems such as fuel cells. Texas could create such a program to encourage businesses to use fuel cells.

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[18] *Pipeline Transportation of Hydrogen: Regulation, Research, and Policy*, Congressional Research Service, March 2021. Retrieved from: https://crsreports.congress.gov/product/pdf/R/R46700

[19] *Under new law, Minnesota gas utilities could play a role in electrification*, Energy News Network, July 2021. Retrieved from: https://energynews.us/2021/07/21/under-new-law-minnesota-gas-utilities-could-play-a-role-in-electrification/

Potential regulatory frameworks that Texas could consider while planning to build a hydrogen hub.

- **Expanding underground storage** warrants revisiting. In March 2022, the Texas House of Representatives interim committee for the Committee on Energy Resources mentioned an initiative to explore options for expanding the state's underground natural gas storage capacity. The committee could consider including hydrogen storage to this initiative.[20]
- **CCS:** The EPA oversees Underground Injection Control (UIC) program requirements, and states can apply for primacy to implement UIC programs. Texas does not yet have primacy for UIC Class VI wells for permanent CO_2 storage. As of June 2021, the Railroad Commission (RRC) has sole jurisdictional regulatory authority over Class VI wells. If the RRC were to seek primacy from the EPA, this move could help to streamline the permitting process, address some uncertainties in permitting, and lay the foundation for future CCS development in Texas.[21]

2. Infrastructure

This section focuses on the infrastructure needed to help develop a hydrogen hub.

Hydrogen storage

Capacity needed

The U.S. has a natural-gas-storage-to-consumption ratio of ~13%, while the global ratio stands at ~11%. This means that the U.S. and the world have ~50 and ~40 days of gas storage, respectively.[22]

This ratio might need to be higher because hydrogen has no natural storage areas. Hydrogen storage demand might be greater than natural gas demand because grid-scale energy storage might require hydrogen to compensate for the intermittency of renewable energy. Texas might need 1-2 MT of storage for hydrogen in 2035 and 2-3 MT in 2050, based on estimated production levels of 8 MT and 21 MT, respectively.

Approaches to acceleration

Since the salt caverns near Houston get heavy use, Texas should investigate the requirements for converting other existing salt caverns to hydrogen storage. Research into bedded salt compatibility with hydrogen storage might be helpful in West Texas for co-location with future electrolysis-based hydrogen production.

Other technical challenges to salt cavern storage include material compatibility, testing requirements, and microbial activities.[23] Additional research will be required to overcome these technical challenges.

2.2. Hydrogen transport

Capacity needed

The 2020 European Hydrogen Backbone study proposed a hydrogen transport infrastructure across ten European countries based mostly on existing energy infrastructure. The analysis estimated being able to develop ~4,200 miles (6,800 km) of hydrogen pipeline by 2030, with ~14,200 miles (22,900 km) in place by 2040. This analysis assumed that 75% of the backbone would be retrofitted natural gas pipelines and the remaining 25% new hydrogen pipelines.[24]

The ten European countries have about 150,000 km of natural gas transmission lines. Assuming that the proposed hydrogen pipeline structure is proportional to the existing natural gas infrastructure suggests that Texas would need a hydrogen transportation network of ~1,500 miles in 2030 and ~5,200 miles in 2040, given its existing network of ~35,000 miles of natural gas transmission pipelines.[25]

Approaches to acceleration and development considerations

The analysis identified three approaches for Texas' consideration.

- **Plan regional or superregional transport and storage system:** Holistic planning for transport and storage infrastructure in a region can enable more rapid development and collaboration.

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[20] *Texas house of representatives 87th legislature, Interim committee charges*, March 2022. Retrieved from: https://house.texas.gov/_media/pdf/interim-charges-87th.pdf

[21] *New Legislation Signals Strong Support for CCUS in Texas*, JD Supra, LLC, June 2021. Retrieved from: https://www.jdsupra.com/legalnews/new-legislation-signals-strong-support-5380562/

[22] *Expert Commentary – The Role of Gas Storage in Balancing Gas Markets in the E.U. and U.S.*, GECF, March 2020. Retrieved from: https://www.gecf.org/events/expert-commentary-the-role-of-gas-storage--in-balancing-gas-markets-in-the-eu-and-us

[23] *Comments by the Center for Houston's Future to the U.S. Department of Energy's Earthshot Request for Information*, Center for Houston's Future, July 2021. See Appendix C for hyperlink.

[24] *European Hydrogen Backbone*, Enagás, Energinet, Fluxys Belgium, Gasunie, GRTgaz, NET4GAS, OGE, ONTRAS, Snam, Swedegas, Teréga, July 2020. Retrieved from: https://gasforclimate2050.eu/wp-content/uploads/2020/07/2020_European-Hydrogen-Backbone_Report.pdf

[25] *Texas Pipeline System Mileage*, Railroad Commission of Texas, 2021. Retrieved from: https://www.rrc.texas.gov/pipeline-safety/reports/texas-pipeline-system-mileage/

For example, the European Hydrogen Backbone Initiative involved 23 gas infrastructure companies in designing a hydrogen network to connect all parts of Europe and allow imports by 2040.

The Port of Rotterdam has announced its intention to build a 24-inch hydrogen pipeline as part of its project HyTransPort.RTM. The project is open access – any company wishing to purchase or supply hydrogen can connect to the pipeline. Its construction will facilitate a hydrogen market in and around Rotterdam, while equipping the port to connect to a larger European hydrogen network in the future.[26]

Texas has ongoing efforts to support holistic infrastructure planning. For example, the H2@Scale project at the University of Texas at Austin is investigating pathways for deploying clean hydrogen in the Texas energy economy. The project team is building a spatially resolved, optimal infrastructure development tool that can locate the lowest-cost, optimal deployment of hydrogen infrastructure to meet future hydrogen demands. The model uses hydrogen demand and willingness to pay and determines the optimal amount of production and distribution infrastructure to meet that demand, if it can also meet the price. Results from this modeling effort will feed into the team's strategic plan and framework for clean hydrogen hub activities in Texas.[27]

- **Cluster physical assets:** Clustering physical assets around production and demand with transport and storage infrastructure could increase utilization and decrease costs. For example, HyNet in the UK plans to build a connected system of low-carbon hydrogen production (Stanlow refinery), CO_2 transport and storage (offshore depleted gas reservoir beneath Liverpool Bay), hydrogen pipeline, salt cavern storage, industrial use, and natural gas blending (Liverpool, Manchester, Warrington, Wigan, and North Cheshire).[28]

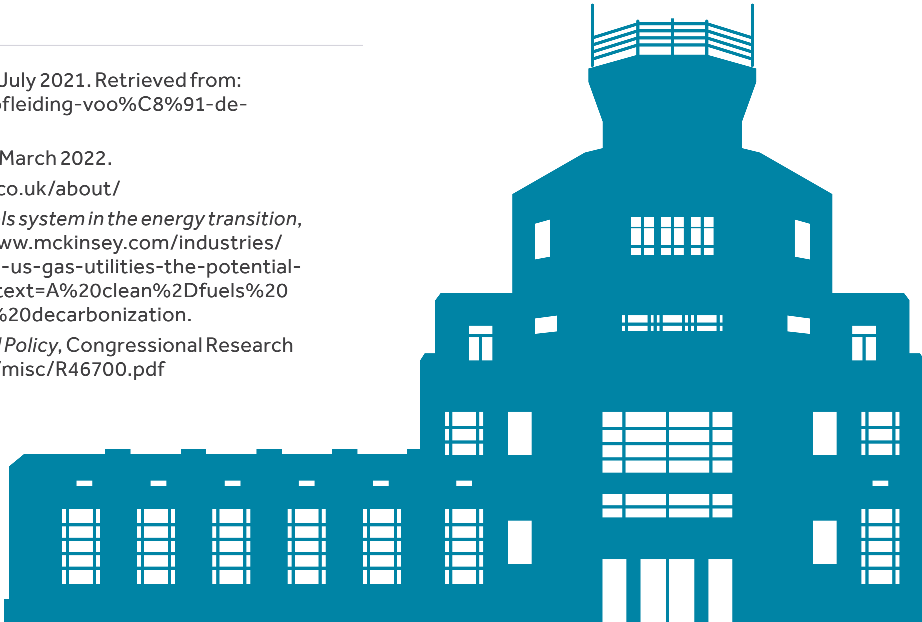
- **Repurpose natural gas infrastructure:** Natural gas utilities could help Texas decarbonize by creating a clean fuels network that complements the renewable energy on the electric grid. Clean fuels such as hydrogen and biogas, used in thermal generation, could help maintain a reliable, resilient power system when renewable energy production is too low to meet demand.

  Utilities are ideally suited to play this role, thanks to their extensive experience developing and maintaining pipelines, navigating regulations, and financing large-scale infrastructure projects. Switching to clean fuels could be cheaper than fully decommissioning the natural gas system and using electrification to meet all energy needs. A clean fuels network in a warm region like Texas could involve total costs 15-25% lower than full electrification.[29] This report identified three challenges to blending hydrogen into pipelines full of natural gas:

  - **Technical challenges:** Current estimates suggest that blending in as much as 20% hydrogen would not require retrofitting pipelines to account for hydrogen's potential to embrittle steel.[30] But pinpointing the upper limit of the "blend wall" needs further research.

  - **Impact on end-use applications:** Household appliances such as stoves, wall heaters, and forced-air furnaces might not be able to handle natural gas blended with hydrogen. Further research is required to understand the impact. Southern California Gas Company recently announced that it is testing the performance of household systems and appliances using a hydrogen blend at a training facility.

    Utilities must also determine where to blend hydrogen into the network to ensure that no hydrogen enters facilities or industrial plants unable



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26 *The hydrogen pipeline for the Port of Rotterdam*, HyTransPort, July 2021. Retrieved from: https://hytransportrotterdam.com/en/de-wate%C8%91stofleiding-voo%C8%91-de-rotte%C8%91damse-haven___/

27 H2@Scale project team at University of Texas at Austin, as of March 2022.

28 *What is HyNet?*, HyNet websit. Retrieved from: https://hynet.co.uk/about/

29 *Decarbonizing U.S. gas utilities: The potential role of a clean-fuels system in the energy transition*, McKinsey & Company, March 2022. Retrieved from: https://www.mckinsey.com/industries/electric-power-and-natural-gas/our-insights/decarbonizing-us-gas-utilities-the-potential-role-of-a-clean-fuels-system-in-the-energy-transition#:~:text=A%20clean%2Dfuels%20system%20could,and%20diversifying%20pathways%20to%20decarbonization.

30 *Pipeline Transportation of Hydrogen: Regulation, Research, and Policy*, Congressional Research Service, March 2021. Retrieved from: https://sgp.fas.org/crs/misc/R46700.pdf

to handle the blended fuel.

- **Regulation:** Regulators would need assurance that blending hydrogen with natural gas is safe and feasible before allowing utilities to proceed.

2.3. Hydrogen fueling network

Capacity needed

Texas might need ~100 hydrogen fueling stations to serve heavy-duty hydrogen trucks by 2030, given the estimated number of those trucks likely to be on the road. The network-building effort could start in the Texas Triangle and expand over time.

Capital expenditures to build a hydrogen fueling station can range from $3 million to $4 million for a station with a capacity of 4,000 kg/day.[31] Texas would have to invest $300 million-$400 million by 2030 to create a fueling network with ~100 stations that could meet heavy-duty truck fueling needs.[32]

Approaches to acceleration and development considerations

This report identified three approaches for Texas' consideration.

- **Connect interstate networks:** A Texas network of hydrogen fueling stations could connect with California via Arizona and New Mexico, especially if the latter becomes a hydrogen hub. This could create a corridor stretching ~2,000 miles from San Francisco to Houston. A network connecting with Louisiana is another possibility, especially if this state becomes a hydrogen hub.[33]
- **Ensure climate equity:** Texas could set tactical and strategic goals to ensure that the benefits reach disadvantaged communities. California's approach will ensure that 94% of the state's population and 97% of its disadvantaged communities sit within a 15-minute drive of a clean fueling station. Municipal buses and vehicles using these fueling stations could further decarbonize city transportation and improve air quality. Texas could replicate this pattern to ensure that the benefits reach disadvantaged communities.
- **Build multi-use stations:** California's fueling stations will cluster around dense urban areas like Los Angeles County and San Francisco, with enough stations along the way to handle long-distance travel. Many fueling stations will serve both light- and heavy-duty vehicles.

2.4. CO_2 transport and storage

Capacity needed

While electrolysis-based technologies will continue to scale through 2050, natural-gas-based pathways will likely represent a significant proportion of hydrogen production. As such, Texas would need significant carbon storage as it transitions into a hydrogen hub. In 2035, the state could produce ~8 MTPA of hydrogen. Assuming that 70-90% of this production is natural-gas-based, Texas would have to store ~45-55 MT of CO_2, based on ATR with CCS at a 98% capture rate.[34]

In 2050, when Texas produces an estimated 21 MT of hydrogen, the storage need would increase to ~50-80 MT of CO_2, assuming that natural-gas-based hydrogen accounts for 30-50% of overall hydrogen production.[35] The percentage of CO_2 captured would remain similar in 2035 and 2050, despite the smaller share of natural-gas-based hydrogen, because of the overall growth in hydrogen production.

In the coming years, companies that can use this captured carbon to manufacture products such as carbon fiber might develop. Texas could benefit from this type of industry, which would consume part of the significant amount of CO_2 expected to be generated and captured in the state.

Approach to acceleration and development considerations

Texas would need to build regional CO_2 transport and storage infrastructure. Decarbonization efforts at industrial centers around the world offer blueprints for building carbon-capture infrastructure.

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[31] Expert interviews.

[32] For comparison, California and Japan are planning to build hydrogen fueling stations for both light-duty and heavy-duty applications. California seeks to build 200 retail fueling stations by 2025 and 1,000 fueling stations by 2030, or one hydrogen fueling station for every eight gas stations that exist today. The state's plan calls for each station to serve 1,000 HFCVs. Japan is taking a similar approach, with a goal of 1,000 fueling stations by 2030, a substantial increase from the 160 operating today.

The California Fuel Cell Revolution, California Fuel Cell Partnership, July 2018. Retrieved from: https://cafcp.org/sites/default/files/CAFCR.pdf.

Japan targets 1,000 hydrogen stations by end of decade, Nikkei Asia, May 2021. Retrieved from: https://asia.nikkei.com/Economy/Japan-targets-1-000-hydrogen-stations-by-end-of-decade#.

[33] *New Mexico to boost clean energy economy with Hydrogen Hub Development Act*, State of New Mexico website, January 2022. Retrieve: https://www.governor.state.nm.us/2022/01/25/new-mexico-to-boost-clean-energy-economy-with-hydrogen-hub-development-act/#.

[34] Assumes ~7-8 kg CO_2 / kg H_2 produced in 2030 for ATR with CCS

[35] Assumes ~7 kg CO_2 / kg H_2 produced in 2050 for ATR with CCS

Six energy companies formed the Northern Endurance Partnership (NEP) in the UK to develop the infrastructure to transport CO_2 and store it offshore in the North Sea. The coordinated carbon capture could provide a model for Texas as it works with industrial facilities spread across the state.

The NEP infrastructure will serve the industrial communities of Teesside and Humber, two of the most carbon-intensive industrial regions in the U.K., by capturing up to 10 MTPA of CO_2 and 17 MTPA of CO_2 in each region, respectively, and transporting the carbon via pipelines to storage sites at least 85 km offshore.[36] The sites can store 450 MT of CO_2 cumulatively, with the possibility of tapping into one billion tons of additional storage areas nearby.[37]

2.5. Other infrastructure needs

Texas could create a digital and financial trade center for the new hydrogen market, similar to the oil and natural gas trading centers that already give Texas a competitive advantage. Current oil and gas trading centers could incorporate hydrogen as a commodity.

Texas would need additional infrastructure to become a hydrogen hub. For example, electrolysis pathways would consume a lot of water that would require purification and transportation to hydrogen production sites as far away as West Texas.

The success of all hydrogen production pathways will depend on having a well-developed port to host infrastructure and a mature supply chain that can provide needed materials, such as cement and steel to build new production facilities.

3. Innovation ecosystem

To build a hydrogen hub, Texas would need an end-to-end innovation system. This report envisions the system having four core components.

3.1. Research consortium

Texas should foster collaboration across institutional lines to develop solutions for a low-carbon future using hydrogen. The hydrogen hub could create a research consortium, drawing researchers from the state's many universities, corporate divisions, and start-ups. Bringing these experts together would equip the hub to tackle the challenges of hydrogen production and lead the world in energy.

3.2. Venture capital/ start-up community

Texas is home to a vibrant venture capital and start-up community. Houston has especially benefited from clean tech funding. In the past five years, almost $1 billion in venture capital has flowed to ~50 Houston-based energy start-ups and companies. In 2021, new energy investments exceeded $630 million more than four times the record set in 2019.[38]

Incubators have helped secure this record investment. For example, Greentown Labs launched in Houston in April 2021 and scaled quickly, having accepted over 60 new start-ups by early 2022. Founded in Boston, Greentown Labs expanded to Houston given the city's engineering strengths, its leading energy companies, and the opportunity to help redeploy Houston's assets to create the energy transition capital of the world.[39]

Houston-based corporate ventures have supported this start-up ecosystem. For example, BP Ventures has invested $500 million in 40 companies.[40] Shell Ventures is making minority investments in companies that help accelerate the energy transition.[41] Baker Hughes Co. has promised to invest $60 million in the FiveT Hydrogen Fund, which is dedicated to scalable, clean hydrogen infrastructure projects.[42]

Universities also play an important role in a hydrogen hub. Rice University's Carbon Hub is researching new applications for clean hydrogen energy, as well as the possibility of sustainably producing advanced carbon materials from natural gas and oil. The University of Houston's Center for Carbon Management in Energy

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[36] *The Northern Endurance Partnership*, Net Zero Teesside website. Retrieved from: https://www.netzeroteesside.co.uk/northern-endurance-partnership/

New collaboration to develop offshore CCUS infrastructure, BP, October 2020. Retrieved from: https://www.bp.com/en/global/corporate/news-and-insights/reimagining-energy/northern-endurance-partnership-to-develop-offshore-ccus-infrastructure.html

[37] *The Northern Endurance Partnership*, Net Zero Teesside website. Retrieved from: https://www.netzeroteesside.co.uk/northern-endurance-partnership/

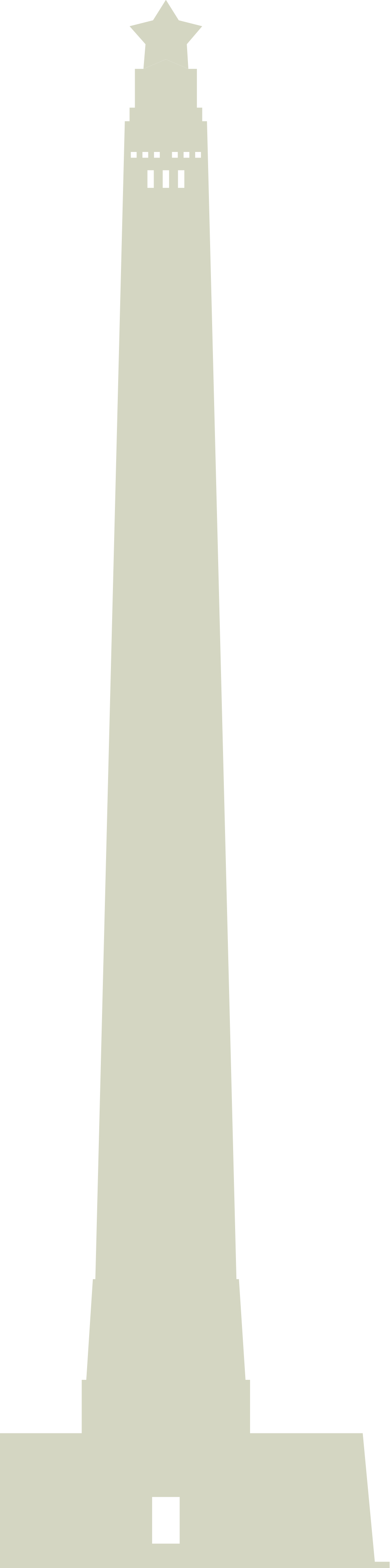
[38] Greater Houston Partnership research team, March 2022.

[39] *Why We're Expanding to Houston, Texas*, Greentown Labs, August 11, 2020. Retrieved from: https://greentownlabs.com/why-were-expanding-to-houston-texas/

[40] *About Us*, BP Ventures website, March 2020. Retrieved from: https://www.bp.com/en/global/bp-ventures/about.html

[41] *Our Portfolio*, Shell's company website, March 2022. Retrieved from: https://www.shell.com/energy-and-innovation/new-energies/shell-ventures/portfolio.html

[42] *Baker Hughes to Become Cornerstone Investor in New Green Hydrogen Fund*, Hart Energy, April 2021. Retrieved from: https://www.hartenergy.com/exclusives/baker-hughes-become-cornerstone-investor-new-green-hydrogen-fund-193338



has focused its R&D efforts on low-carbon energy. The University of Texas' Center for Electromechanics is participating in the H2@Scale project.

3.3 Test facility

New hydrogen solutions require testing before scaling and commercialization. But innovative technologies that emerge from, say, a university often struggle to find industry partners to help commercialize the discovery. The issue is lack of testing, including its associated capital and equipment. Many start-ups face similar challenges in securing the requisite wet labs and testing facilities in their early stages.

A testing facility can help bridge the gap between the lab and the market by offering a place to fine-tune new technologies for eventual use in large-scale applications. A hydrogen ecosystem in Texas could connect start-ups and incubators with emerging technologies, reducing the risk and cost of the typical lab-to-market process.

The H2@Scale project in Texas has provided testing opportunities and would need further scaling. Mitsubishi's Takasago Hydrogen Park in Japan might demonstrate a path forward. This testing facility can oversee every step of a technology's journey to market, including research, design, prototype production, and validation testing.[43]

3.4 Equipment manufacturing

Local manufacturing of hydrogen production equipment, including but not limited to electrolyzers, would help create an end-to-end innovation system in Texas. This integrated supply chain could also reduce costs, further integrate the hydrogen production supply chain, and create more local jobs.

4. Equitable workforce development

The transition to hydrogen could create ~180,000 jobs, including direct, indirect, and induced jobs.

Direct jobs participate directly in the hydrogen economy. They include jobs in the manufacturing of equipment to produce and distribute hydrogen; hydrogen production, distribution, and infrastructure; and the manufacturing of specialized materials and components.

Indirect jobs support the hydrogen economy. They include maintenance, legal contracting, and administrative support.

Induced jobs are created by the spending that direct and indirect jobs make possible. They include jobs in entertainment, health care, and restaurants.

Workers in the oil and natural gas industry could fill many of these jobs. Texas could lose ~150,000 jobs from 2020-50 under the Further Acceleration scenario (see section 3.1). However, aggressively pursuing opportunities like those associated with the hydrogen hub and other energy transition technologies could fill this gap. In fact, ~180,000 represents the upper bound of the number of jobs that the hub-building effort could reskill. In other words, the hydrogen economy could net 30,000 more jobs.

Texas should consider three additional sources of hydrogen workers.

- **Community college programs** would require scaling to meet the hydrogen employment demand in the state and beyond. The Texas Reskilling and Upskilling through Education (TRUE) program, passed by the state legislature in June 2021, could support scaling efforts.[44] In

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[43] *Mitsubishi Power to Establish Hydrogen Power Demonstration Facility Takasago Hydrogen Park at Takasago Machinery Works*, Mitsubishi Power, February 2022. Retrieved from: https://power.mhi.com/news/20220222.html

[44] *Texas Senate Bill 1102*, Texas Legislature website. Retrieved from: https://capitol.texas.gov/tlodocs/87R/billtext/html/SB01102F.HTM

the spirit of the Justice40 Initiative, this training should ensure that disadvantaged communities have access to these well-paying jobs with good labor standards.

- **Partnerships between industry players and educational institutions** could also help develop the hydrogen workforce. Shell and Prairie View A&M University signed a $6 million renewable energy research partnership that will emphasize carbon capture and utilization, while creating a new hiring pipeline for Shell.[45] Houston and CenterPoint Energy recently announced *Resilient Now*, a collaboration to advance economic development in vulnerable communities in the greater Houston area and provide clean energy job training.[46]
- **Higher education curriculums** should start planning for tomorrow's jobs today. Texas already has efforts underway to train people for the hydrogen economy. The new University of Houston Energy Transition Institute will focus on clean energy such as hydrogen while benefiting communities affected by climate change.[47] The University of Houston also offers a stand-alone micro-credential program on the hydrogen economy for energy professionals.[48]

Texas should also ensure that new hydrogen jobs are accessible to residents of disadvantaged communities, through incentives and targeted efforts to employ as many people directly from disadvantaged communities as possible. Academic institutions and employers should collaborate on training and recruiting students and workers from such communities to fill those jobs.

In the near term, Texas could convene industry players and educational institutions to identify future hydrogen-hiring needs and develop programs tailored to serve disadvantaged communities. Texas could also require hydrogen educational and retraining programs to have over 40% representation from disadvantaged communities, in keeping with the spirit of the Justice40 Initiative, and could implement best practices and accountability measures for companies to increase hiring from such communities.

In the long term, Texas could consider requirements and incentives for 80% of companies in the hydrogen value chain to hire over 40% of their local workers from disadvantaged communities. Eventually, this requirement could apply to 100% of companies in the hydrogen value chain.

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[45] *PVAMU, Shell to explore renewable energy through new $6 million farming research project*, Prairie View A&M University, January 2022. Retrieved from: https://www.pvamu.edu/blog/pvamu-shell-to-explore-renewable-energy-through-new-6-million-farming-research-project/

[46] *City of Houston and CenterPoint Energy Announce Transformative Initiative to Enhance Energy Resilience and Promote Transition to Sustainable Energy*, City of Houston, February 2022. Retrieved from: https://www.houstontx.gov/mayor/press/2022/centerpoint-sustainable-energy.html

[47] *University of Houston Creates Energy Transition Institute with $10 Million Commitment from Shell*, University of Houston. Retrieved from: https://stories.uh.edu/2022-energy-transition-institute/index.html

[48] *The Hydrogen Economy Program*, University of Houston. Retrieved from: https://uh.edu/uh-energy/sed-program/hydrogen/

7 Next steps

As efforts to envision a Texas-based hydrogen hub mature, further analyses will be crucial to understanding its implications for the economy and the climate. These include quantification of carbon reduction benefits from proposed projects; more granular cost comparisons of different methods of hydrogen storage and transport; and study of the cost of intermediate storage, potential optimization of power costs by utilizing both wind and solar, and changes in demand sources over time. Analyses should also explore additional factors such as securing a pure water supply; the lifecycle and selection of system components; supply chain constraints and prices for rare-earth metals (particularly important for electrolyzers); direct demand for hydrogen-fired power generation, as opposed to gas blending; and cost fluctuations from varying grades of hydrogen (from carrier/storage conversion) determined by end-use purity attributes.

The next phase of this effort will build on this report's analysis and call for actions, especially to accelerate demand creation, that will jumpstart building the hydrogen hub from 2022 through 2030. The effort will focus on answering the following questions:

1. What three to five demand sectors should the hub target to build clean hydrogen demand in the short term? What are specific areas to enhance value creation for the hub, especially with exports?
2. What is the hub's path to achieve unique cost competitiveness?
3. What are the end-to-end pilot projects and shared infrastructure required to bring the demand identified to life?
4. What is the economic, social, and environmental impact from these projects such as emissions abatement?
5. What are the appropriate hub funding requirements and mechanisms required for the hub to take off?
6. What sequencing of supply, demand, and infrastructure build up is necessary to expand and scale the hub?
7. What is the right coalition to drive an integrated effort for the development of the hub?

8

Conclusion

Texas and the Houston region are strong candidates for developing a regional clean hydrogen hub. The state's concentration of energy and petrochemical players, geological advantages, access to multiple ports, highly skilled workforce and extensive hydrogen pipeline infrastructure, position Texas to become a global leader in the new hydrogen economy. The hydrogen hub could be pivotal in helping Texas build a more resilient, diversified economy that is well-equipped for the future, while mitigating the emissions footprint of the state's industrial corridors.

A hydrogen hub could have significant economic impact and reduce emissions. The hub promises to add $100 billion of economic value, create ~180,000 jobs in the region, and abate 220 MTPA of CO_2 by 2050.

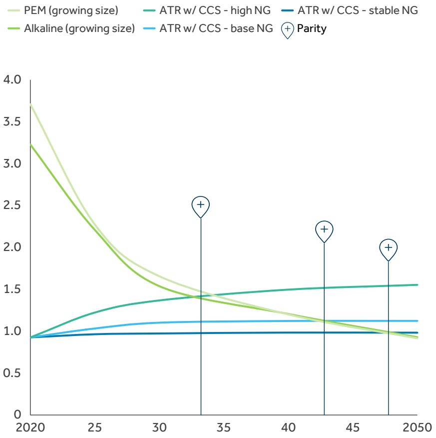
The momentum for the energy transition in Texas is stronger than ever. Over 150 businesses, academic institutions, nonprofits, and individual experts have been working together in the HETI Hydrogen Working Group, led by the Center for Houston's Future, to study the viability of such a hub in Texas.

Appendix

Appendix A: Additional analysis

Natural-gas-based production costs are sensitive to natural gas costs

Texas hydrogen natural gas price sensitivity, $/kg



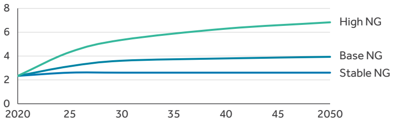
Source: McKinsey Hydrogen Insights

Assumptions

Scenarios

- Stable NG scenario: ~$2.5-$3/MMBtu prices throughout the period
- Base NG scenario: IEA AEO 2021 reference case, reflects NG production recovers to pre-Covid levels in 2024 and increase at a modest rate through 2050
- High NG scenario: IEA AEO 2021 low oil & gas case, reflects minor decline in total domestic production of NG from 2025 to 2050

Natural gas prices, $/mmbtu



Takeaways

In the example pathways modeled, hydrogen cost parity between technologies would be expected in 2045-2050 given $2.5-$3/MMBtu natural gas prices.

However, parity would be accelerated to 2040-2045 if natural gas prices reach $4/MMBtu, and further accelerated to 2030-2035 if natural gas prices reach $5/MMBtu and above

Appendix B:
Assumptions behind the LCOE values used in the model

Table 1: Two LCOE scenarios used as inputs in calculating renewable energy costs

Year	2020	2025	2030	2040	2050
High LCOE, USD/MWh	~37	~31	~26	~21	~18
Low LCOE, USD/MWh	~28	~23	~21	~17	~13

The analysis in this report used two Texas-specific LCOE scenarios for wind energy to calculate the cost of electricity when producing electrolysis-based hydrogen. The low LCOE values were based on the following assumptions:

1. The LCOE uses "the top quartile for wind in Texas," which means the LCOE is an average of some of the most favorable wind speeds in the state.
2. Wind turbines have a 15% learning rate on capex per global doubling of deployment; analysis assumes that this rate will hold through 2050
3. The LCOE aligns with the Further Acceleration Scenario, as defined in the McKinsey Global Energy Perspective, February 2022

For context, the U.S. Department of Energy estimates that the average LCOE for wind in the United States for 2020 was $33/MWh with ERCOT enjoying $29/MWh. (Source)

The Annual Technology Baseline from the National Renewable Energy Lab estimates that the best locations in the United States currently enjoy LCOEs of $26/MWh and could reach $14/MWh in 2030. (Source)

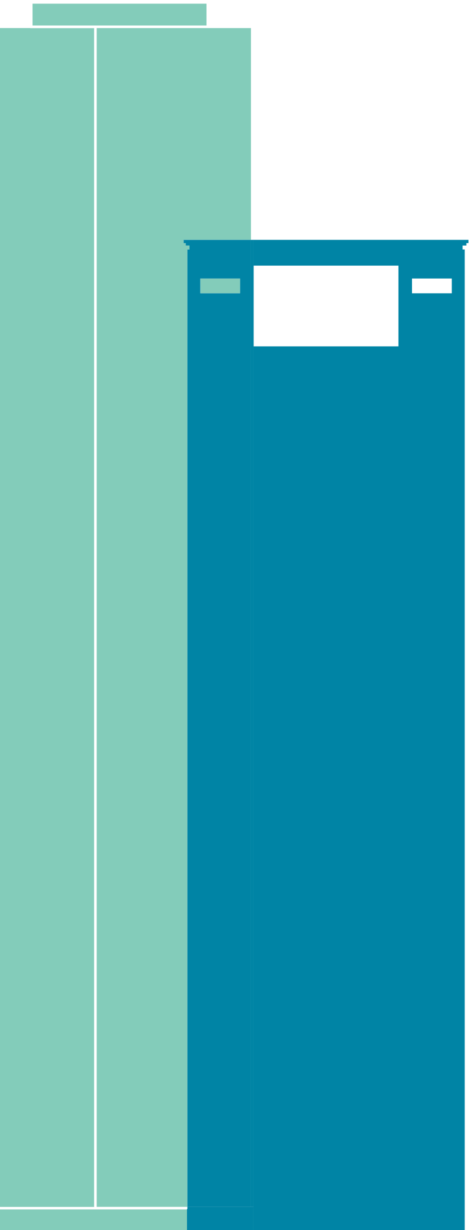
The high-LCOE scenario uses a general average for the region.

Appendix C. Key references

This report builds on a rich body of previous research, especially the following publications:

1. *Global Hydrogen Review 2021*, IEA, October 2021. (Source)
2. *Hydrogen Insights Report 2021*, Hydrogen Council, McKinsey & Company, July 2021. (Source)
3. *Hydrogen Blending in Texas Natural Gas Power Plants at Scale*, The University of Texas at Austin, H2@UT, January 2021. (Source)
4. *Houston: The Low-Carbon Energy Capital*, University of Houston, October 2020. (Source)
5. *Evaluating Net-Zero Industrial Hubs in the United States: A Case Study of Houston*, Columbia University, Center on Global Energy Policy, June 2021. (Source)
6. *Green hydrogen cost reduction: Scaling up electrolysers to meet the 1.5°C climate goal*, IRENA, December 2020. (Source)
7. *Renewable Electrolysis in Texas: Pipelines versus Power Lines*, The University of Texas at Austin, H2@UT, August 2021. (Source)
8. *European Hydrogen Backbone*, Enagás, Energinet, Fluxys Belgium, Gasunie, GRTgaz, NET4GAS, OGE, ONTRAS, Snam, Swedegas, Teréga, July 2020. (Source)
9. *Hydrogen for Net Zero: A critical cost-competitive energy vector*, Hydrogen Council, November 2021. (Source)
10. *Hydrogen scaling up: A sustainable pathway for global energy transition*, Hydrogen Council, November 2017. (Source)
11. *The Technical and Economic Potential of the H2@Scale Hydrogen Concept within the United States*, The National Renewable Energy Lab, January 2021. (Source)
12. *Comments by the Center for Houston's Future to the U.S. Department of Energy's Earthshot Request for Information*, Center for Houston's Future, July 2021. (Source)
13. *Road Map to a U.S. Hydrogen Economy*, FCHEA, October 2020. (Source)
14. *Pipeline Transportation of Hydrogen: Regulation, Research, and Policy*, Congressional Research Service, March 2021. (Source)
15. *Business Models for Carbon Capture, Usage and Storage*, Department for Business, Energy, & Industrial Strategy, September 2019. (Source)

Detailed citations of all sources appear in the footnotes.



Appendix D. Introduction to HETI and CHF

HOUSTON ENERGY TRANSITION INITIATIVE

Houston has a long history of solving many of the world's greatest challenges – developing medical breakthroughs, leading human spaceflight, and powering the world – we are a city of problem solvers and innovators who tackle big, complicated, and consequential problems.

Houston is being called again to solve a global challenge of extreme magnitude: how to meet growing global demand for energy while simultaneously dramatically lowering climate changing greenhouse gas emissions.

The challenge of our time is the Energy Transition. Solving it – developing and scaling the right technologies, creating and servicing markets for the right mix of energy sources, investing in the right energy priorities – is the challenge and opportunity that Houston is determined to embrace and lead.

The Greater Houston Partnership's effort to develop a regional energy transition strategy was informed by an intensive study to understand how the region should best tackle the challenge. The Partnership's objective was to create a vision and a blueprint for growing the region's economy, equitably creating new jobs, exporting low-carbon products and expertise, and helping Houston achieve its net-zero emissions target that is core to the City's Climate Action Plan.

Drawing on strategic analysis and recommendations from McKinsey & Company, the work of the Center for Houston's Future, University of Houston and more than 60 leaders from across business, academia and public sectors, the Partnership has launched a critical initiative with an ambitious vision:

Leverage Houston's energy leadership to accelerate global solutions for a low-carbon future.

The Houston Energy Transition Initiative (HETI) is rooted in the city's eagerness for innovation; its appetite for high-risk and high-reward business investments; and its capacity for executing on massive, complex projects around the world. It also leverages Houston's deep experience and infrastructure in producing, moving, financing and marketing energy in all its forms.

This effort represents Houston's collective ambition. But it also reflects Houstonians' sense of responsibility for putting their capabilities and resources to work on global solutions to the climate and energy challenges. HETI builds on the best of traditional energy skills and systems to pave the way for a new 21st century low-carbon world.

CENTER FOR HOUSTON'S FUTURE

Center for Houston's Future (CHF), an independent affiliate of the Greater Houston Partnership, focuses on understanding future global trends and their impact on the Houston region. CHF brings business, government and community stakeholders together to engage in fact-based strategic planning, collaboration, and action on issues of great importance to the success of our region.

Appendix E. Tools and capabilities deployed

The report used several McKinsey & Company tools and capabilities.

McKinsey Global Energy Perspective (GEP) is a global market intelligence and analytics group focused on the energy sector. GEP enables organizations to make well-informed strategic, tactical, and operational decisions, using an integrated suite of market models, proprietary industry data, and a global network of industry experts. GEP works with leading companies across the energy value chain to help them manage risk, optimize their organizations, and improve performance.

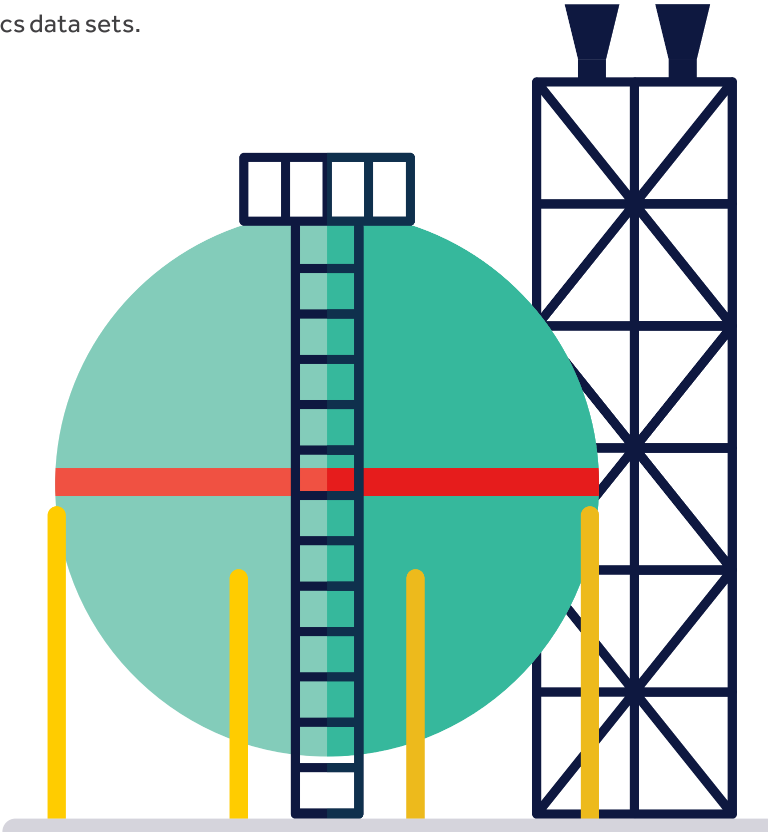
McKinsey Hydrogen Insights is a dedicated team of global experts that helps organizations participate in and scale up the clean hydrogen economy and combat climate change. Hydrogen Insights provides more than five established assets combining deep macro-level insights in the hydrogen ecosystem with highly individualized cost perspectives. The Hydrogen Insights Cost Model combines energy and hydrogen-demand projections with regionally specific cost and supply dynamics and was used to support the analysis for this perspective. The model develops detailed cost outlooks for underlying technologies such as electrolyzers; fossil reforming; renewables cost decline; and carbon capture, transportation, and storage.

McKinsey Power Model projects capacity additions in the power sector and simulates dispatching decisions based on system-cost optimization.

McKinsey Center for Future Mobility brings a forward-thinking and integrated perspective–covering automotive, cities, freight, infrastructure, last-mile delivery, utilities, and others–to help industry leaders and policymakers lead change and navigate an increasingly autonomous, connected, electrified, and shared future.

McKinsey CO_2 Emissions Database aggregates global industrial CO_2 emissions from over 21,000 facilities across 11 sectors. The emissions data supports examination of potential CCUS clusters, testing of CO_2 pipeline networks, and understanding of regional abatement costs.

McKinsey CCUS Cost Model takes an end-to-end approach to model carbon capture, compression, transport, and storage. It combines publicly available data, in-house expertise, and benchmarks from McKinsey's proprietary Energy Insights and Westney Capital Analytics data sets.



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