# CENTER FOR HOUSTON'S FUTURE



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Wednesday, July 7, 2021

U.S. Department of Energy
1000 Independence Ave SW
Washington, DC 20585

Re: HFTO RFI (DE-FOA-0002529/Hydrogen Energy Earthshot)

Please find enclosed comments by the Center for Houston's Future on DOE's Hydrogen Energy Earthshot initiative to enable low cost, clean hydrogen at scale.

**Sincerely,**

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**"We choose to go to the moon. We choose to go to the moon in this decade and do the other things, not because they are easy, but because they are hard...."**

**"[T}this 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, Sept. 12, 1961[1]

***"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."***

*U.S. Energy Secretary Jennifer Granholm, Visit to Houston, June 1, 2021*[2]

**"Throughout the United States there is a hunger today for another 'Moonshot,' some shared national endeavor that will transcend partisan politics. If Kennedy put men on the moon why can't we eradicate cancer, or feed the hungry or wipe out poverty or halt climate change?"**

*American Moonshot: John F. Kennedy and the Great Space Race* by Rice Historian Douglas Brinkley

## Comments by the Center for Houston's Future to the U.S. Department of Energy's Earthshot Request for Information

The Center for Houston's Future, a Houston-based nonprofit that looks "over the horizon" at the future of the Houston region, is pleased to submit these comments[3] to the Department of Energy making the case that Houston should be a site for a DOE hydrogen demonstration project, which will help achieve DOE's vision for tackling the toughest problems to deploy clean energy technologies at scale.[4]

Just as President Kennedy's historic Moonshot speech at Rice University in 1961 set the vision for landing on the moon in a decade, now sixty years later, U.S. Energy Secretary Granholm has

[1] https://er.jsc.nasa.gov/seh/ricetalk.htm
[2] https://www.energy.gov/articles/icymi-secretary-granholm-touts-american-jobs-plan-clean-energy-jobs-houston
[3] We are developing a list of organizations who support these comments and will submit a supplemental list.
[4] https://www.energy.gov/articles/secretary-granholm-launches-hydrogen-energy-earthshot-accelerate-breakthroughs-toward-net

launched the Energy Earthshot and the ambitious Hydrogen Shot goal of 1 by 1 by 1 (reducing the cost of hydrogen to $1/kg in 1 decade), a similarly bold vision that will transform our energy system and address climate change.

And, just as President Kennedy recognized Houston "was not built by those who waited," we believe that as the Energy Capital of the World, Houston is both "ready to move forward" and the logical place, as Rice University historian Douglas Brinkley has said, to "once again do bold things" by addressing climate change.[5]

We believe Houston has all the characteristics needed to support the Department's Earthshot vision of dramatically lowering the cost of hydrogen to $1/kg in one decade, reducing carbon emissions and local air pollution, creating good-paying jobs and benefiting disadvantaged communities.

**The Center for Houston's Future Role in Accelerating the Region's Development of Low Carbon Energy**

The Center for Houston's Future, an independent twenty-year-old non-profit affiliated with the Greater Houston Partnership (the Houston region's major economic development organization), focuses on understanding future global trends and their impact on the Houston region, and, then, working with community, business and government partners, seeks to spur actions to improve Houston's presence as a major global city.

Against the backdrop of climate change and Houston's leading position as the world's energy capital, the Center has been a pioneer in recognizing that Houston can and should become the "low-carbon" energy capital and has undertaken research, conferences, webcasts, projects, work with partners and other activities to catalyze this vision.

As a result, we've identified multiple opportunities in low-carbon hydrogen to build on Houston's asset base, on the expertise of Houston energy companies and on the region's trained and skilled workforce, including a depth of energy engineering and professional services.

We believe that Houston, given these unique assets, can play a positive role in lowering carbon emissions from existing hydrogen production, in pioneering new ways of producing hydrogen

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[5] On the 50th anniversary of the moon landing, Prof. Brinkley suggested that:

> .... most Americans want a moon shot, they want to get out of this horrible fighting and beating of each other, right versus left, and unify behind something big and bold that will make all Americans proud. So, there's still more than nostalgia on Apollo 11, it's a kind of a fig leaf of hope that in the coming decades the United States can once again get their act together and do big bold things like we used to do.

Transcript: Douglas Brinkley on "Face the Nation," July 14, 2019. https://www.cbsnews.com/news/transcript-douglas-brinkley-on-face-the-nation-july-14-2019/

through the many "colors" of hydrogen and in expanding into new applications and uses for hydrogen.

We recognize that this issue is urgent from climate change and competitive standpoints.

Texas has experienced many "exceptional" weather events (unusual storms, heat waves, cold weather occurrences and hurricanes) that are now becoming all too frequent, such as Hurricane Harvey, several "500 year" floods (the so-called Tax Day and Memorial Day floods) and the unexpected freeze that led to the February 2021 energy blackout. These have occurred at such an increasing frequency that they can no longer be attributed to simply random occurrences.

Addressing climate change is an urgent global imperative and the need to develop the tools for new climate solutions has never been higher.

In that context, a shift to hydrogen has gained much attention. Since the start of 2020, multiple regions have developed strategies to use $H_2$ in achieving decarbonization goals, including the European Union, Australia, Japan and several European countries (Germany, the Netherlands, Norway, Portugal, Spain and France).

Those plans have increased the focus on the unique and multiple potential roles of $H_2$ in a low-carbon energy system. That, in turn, explains why the market for $H_2$ gas and related equipment is projected by the Hydrogen Council to grow five times to reach $2.5 trillion by 2050.

Houston, home to the largest global energy cluster encompassing over 4,600 energy companies, is embracing both the decarbonization challenge and the opportunity to become a leader in the energy transition. Many Houston-based energy companies, as described in these comments, are making low-carbon commitments and beginning to formulate plans for hydrogen projects to help meet their commitments.

Just last week, on June 29-July 1, 2021, the Center and Greater Houston Partnership unveiled its comprehensive strategy at a widely attended three-day conference focused on how Houston might lead the globe in the Energy Transition.[6] As part of the launch, the Center hosted an event featuring hydrogen experts from across the globe to discuss how Houston, already a global center of hydrogen production and expertise, can transition to a low-carbon hydrogen hub.[7] That low-carbon vision, called H2Houston Hub, is discussed in our comments.

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[6] Greater Houston Partnership Launches Regional Energy Transition Strategy https://www.houston.org/news/greater-houston-partnership-launches-regional-energy-transition-strategy

[7] Day 3 of Future of Global Energy: Hydrogen's Role in the Transition, https://www.houston.org/news/day-3-future-global-energy-hydrogens-role-transition

In undertaking this effort, the Center is working closely with many collaborators. In particular, University of Houston and consulting firm KPMG have been key partners in conducting invaluable assessments of Houston's low-carbon energy opportunity set.

As a result of this work, the Center has identified multiple opportunities to expand clean hydrogen value chains in Texas and to develop a vision and roadmap to enter and expand new markets for hydrogen.

As will be discussed in detail below, the Houston region already leads the nation in existing hydrogen production and use. Hydrogen in the Houston Gulf Coast region is predominantly used for oil refining and petrochemical feedstock. We can leverage this unmatched set of assets to help decarbonize the region and to become a capital for advancing the global role of low-carbon hydrogen to address the world's climate challenge.

**Houston's Competitive Advantages in Creating a Low-Carbon Hydrogen Hub**

Houston, renowned as a global leader in energy, is home to multinational and local companies with broad experience in developing and deploying large-scale energy technologies and delivery systems.

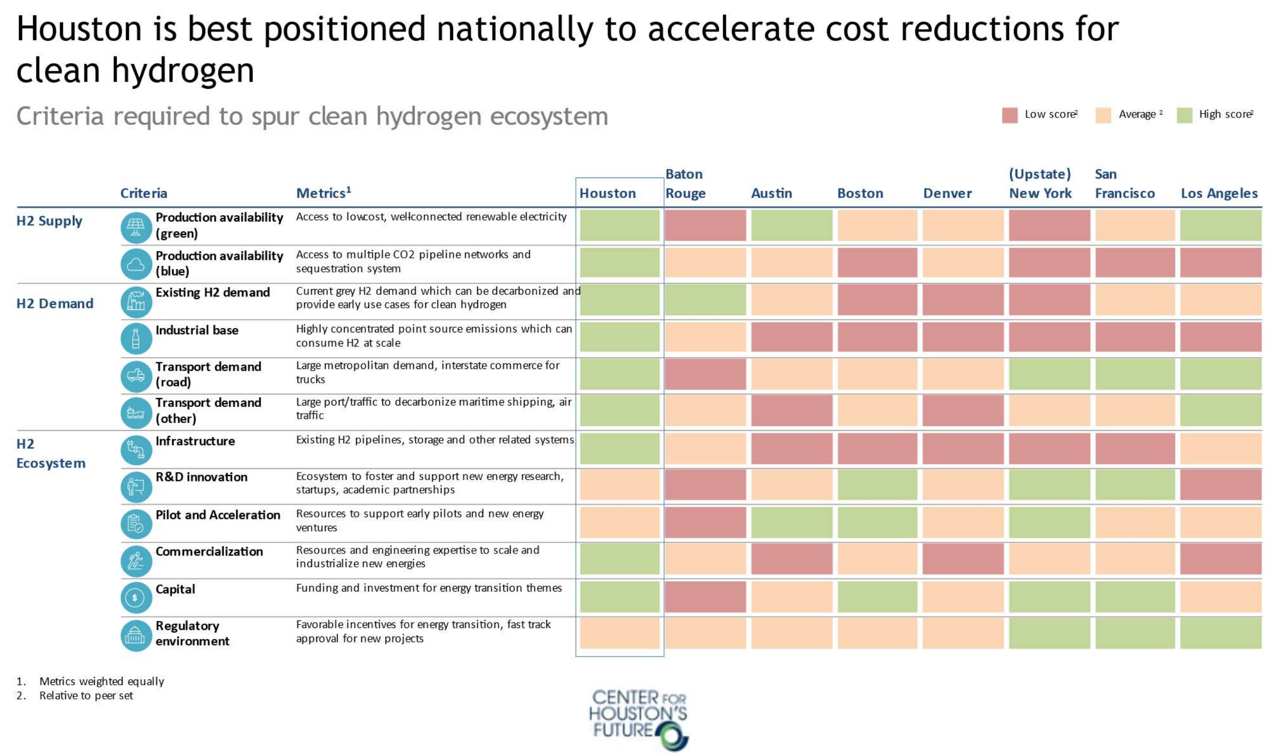
The expertise of the Houston energy community is essential for not only decarbonizing existing energy assets but also for developing cleaner forms of energy. And, expertise in developing and deploying technology at scale will be a key to decarbonizing large segments of the energy economy.

For example, Houston is home to R&D and technology companies with deep expertise in carbon capture and storage; production and distribution of hydrogen; offshore structures that can be adapted for wind energy; transformational technology for refining and chemicals to that will allow the use of hydrogen for process heat; and the recycling of plastic waste.

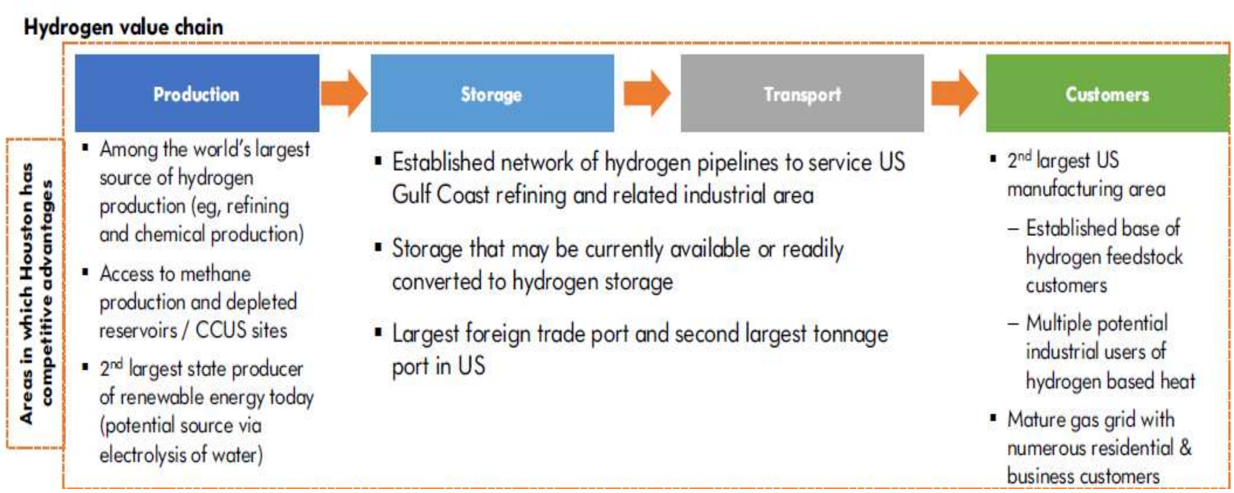
The chart below shows how Houston compares to regions across the nation in terms of its competitive advantages across several dimensions, including hydrogen supply, hydrogen demand and the hydrogen ecosystem.

The chart also suggests a set of criteria the Department of Energy could consider in evaluating demonstration projects. And, it summarizes why we think Houston is so well positioned to assist the Department of Energy with its goal of dramatically lowering the cost of producing and distributing hydrogen.

On the supply side, these include the potential for all forms of clean hydrogen and, on the demand side, include existing and future demand. In terms of the ecosystem, factors to consider include infrastructure, innovation environment, state and local policies, and access to capital. In addition, community engagement and environmental justice considerations could be added.




As shown on the chart below, the Houston region has significant competitive advantages across the hydrogen value chain. Our advantages in low production costs, clusters of pipeline and transport infrastructure and sophisticated end-use customers all are likely to create a favorable business case for hydrogen projects.



With the above in mind, we will describe how the Department of Energy should proceed as it considers demonstration projects to accelerate the development of hydrogen hubs, and why we believe Houston should be a site for such a demonstration project.

**Regional Hydrogen Production, Resources, and Infrastructure**

1. Please describe specific ideal regions to support a hydrogen demonstration project which have the necessary resources available for clean hydrogen production and infrastructure, including, but not limited to water, renewables, nuclear, natural gas (with CCS) or other energy resources captured from waste streams (e.g., landfill, flare gas, wastewater treatment).

a. How much hydrogen could be produced (in tonnes per day and per year) and from what resources? State the amount of each resource available, including water as required.

b. Is there any existing hydrogen infrastructure or infrastructure that could be repurposed as part of a hydrogen demonstration? State specific location if available.[8]

In this section, we describe how Houston can leverage its current position as a leader in low-cost hydrogen production to meet the DOE's Earthshot goals of creating low-cost and low-carbon hydrogen production. (Question 1.a.). We also show that Houston's unparalleled energy and hydrogen infrastructure could be employed to lower the delivered cost of low-carbon hydrogen locally, nationally and globally. (Question 1.b.).

The Houston Gulf Coast region is home to the most extensive and tightly clustered network of hydrogen production in the nation.

Overall, the U.S. produces 11 million metric tonnes (MMT) annually of hydrogen and the Texas Gulf Coast anchors one of the world's leading H2 systems, producing one third of U.S. total $H_2$ gas per year.

Today, this system primarily serves the U.S. Gulf Coast's refining and petrochemical industry, which comprises approximately 30% of U.S. refining capacity and more than 40% of U.S. petrochemical capacity. This system encompasses an expansive network of 48 $H_2$ production plants. Most of these plants now use steam methane reforming (SMR) to produce hydrogen.

The Houston region's industrial sector accounts for 40% of Texas' industrial CO2 emissions, totaling 65 metric MMT annually. Of that amount, the current "gray" hydrogen system produces about a quarter of the industrial CO2 emissions in the Houston region.

As discussed in detail in Section 3 of these comments, these plants can be retrofitted for carbon capture. Moreover, newer technologies (such as Autothermal Reforming (ATR) or Partial Oxidation (POX)) will allow a higher percentage of CO2 capture and can leverage the base of existing Houston facilities.

[8] Questions 1.a and 1.b are answered together.

Given the magnitude of the existing asset base and the decarbonization challenge, the Center, along with its partners at the University of Houston, developed a three-prong strategy for how we might develop into a global low carbon hydrogen hub, which we discuss in Section C. [9]

We also discuss in Section 3 how the significant infrastructure in the nine-county Houston region is the key to accelerating deployment of carbon capture technology. The Denbury Greencore Pipeline, with 13 million tons/year in available capacity to transport CO2, would be available for carbon capture projects. Geologic storage is accessible to the Gulf coast and can receive 1.4 billion tons of CO2 for enhanced oil recovery and an additional 1.5 trillion tons into saline formations.

In addition, as shown in the figure below, there are more than 900 mi of $H_2$ pipelines (more than half of the U.S. $H_2$ pipelines and one third of $H_2$ pipelines globally). As discussed below, Houston has geologically unique and at-scale salt cavern storage**.** This extensive dedicated hydrogen network will be important for lowering the delivered cost of hydrogen.


**FIG. 4.** Existing $H_2$ system in the U.S. Gulf Coast region. Sources: H2Tools, USDOT–PHMSA, Air Liquide, Air Products, Praxair.

As discussed in the applications section, we believe the existing system can meet any short-term needs for new applications given the small incremental amount of hydrogen required, and that there would be ample expansion capacity as demand increases.

[9] Becoming a Global Hydrogen Hub, https://www.centerforhoustonsfuture.org/s/Houston-Hydrogen-Whitepaper-Final.pdf

Our work has included developing the complete vision for how we might build a hydrogen hub over the long term. [10]

Our comments below focus on the initial demonstration activities to facilitate the hub's development and then discuss how a regional demonstration project could set Houston up for achieving that long-term vision.

**Demonstration Opportunities:** We see several initial opportunities for Houston to develop a hydrogen demonstration production hub. We show how we can assist DOE in meeting its Earthshot challenge, which seeks to "unlock a five-fold increase in demand by increasing clean hydrogen production from pathways such as renewables, nuclear, and thermal conversion." But there are significant opportunities to decarbonize existing hydrogen production as well as lowering the cost of newer forms of hydrogen production.

We recommend that the Department consider both strategies in evaluating demonstration projects. A "technology neutral" framework that focuses on the carbon intensity of the hydrogen produced rather than on just the means of hydrogen production will help the United States and the world achieve its decarbonization goals faster. Indeed, as current research shows, a focus in the short term solely on the means of hydrogen production can sometimes lead to unexpected outcomes.[11] By focusing on lowering carbon intensity in its demonstration projects, the DOE can achieve the lowest cost hydrogen at scale in the shortest time frame.

We discuss below how several strategies could be employed in a Houston regional demonstration project to achieve this goal.

Evolving from an existing gray $H_2$ to a blue $H_2$ system: We see opportunities to decarbonize existing hydrogen production by focusing on those SMR plants that are the best candidates for CCS equipment.

Houston has already been the site of the largest CCUS project by an industrial gas company. The plant captures CO2 from two retrofitted steam methane reformers at a Port Arthur refinery. It has captured over six million tons of CO2. [12]

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[10] The Center's vision for developing a low carbon global hydrogen hub has been covered extensively. See, Center Vice Chair Andy Steinhubl's article, Transforming Texas into a Global Hydrogen Hub https://www.nxtbook.com/nxtbooks/gulfpub/h2tech_q2_2021/index.php#/p/28 and Texas could become nation's leader in production of hydrogen energy, Houston Chronicle, Feb 15, 2021 https://www.houstonchronicle.com/business/texas-inc/article/Texas-could-become-nation-s-leader-in-15941151.php

[11] For example, a Bank of America research report shows that, even in CA, where the penetration of renewables is 32%, the carbon intensity of electrolysis is currently higher than that of SMR produced hydrogen. https://rsch.baml.com/r?q=jYMVrWVsF8RqJVzn7MxjlA&e=bperlman%40futurehouston.org&h=2MIgmw

[12] https://www.airproducts.com/news-center/2021/01/0127-air-products-and-industry-leaders-discuss-road-to-us-hydrogen-economy

As discussed in Section 3 and in the University of Houston's carbon capture report[13], we have identified the initial plants we believe will provide an opportunity to leverage the existing hydrogen system by coupling gray $H_2$ production with carbon capture. These first plants would let us develop the potential to bring substantial volumes of $H_2$ to new markets rapidly and at scale.

In creating this strategy, we roughly followed the three-phase approach adopted by the National Petroleum Council's Report to the Department of Energy on carbon capture that looked at an "activate-expand-rollout" model for CCS deployment. [14]

By using existing hydrogen infrastructure and abundant natural gas resources, the Houston region produces **grey** hydrogen for as low as **$.85/kg** (S&P)[15] - $1.18/kg (NREL)[16].

For the initial phase of the deployment, we estimate the cost of adding CCS equipment to SMR for **blue** hydrogen production is in total **$.50/kg**. We estimate the capital cost of CCUS to be $20 per ton of $CO_2$, and operational cost to be $25.5 per ton of $CO_2$.[17] This is an equivalent of **$0.46 per kg of H2,** [18] which is more conservative than *Great Plans Institute's* estimate of $0.39 per kg of H2.[19]

Clearly, incorporating strategies for decarbonizing existing SMR assets in DOE's hydrogen demonstration project design will have the benefits of both accelerating the regional decarbonization effort and lowering the cost of developing and implementing carbon capture technologies. [20]

DOE's Earthshot clearly seeks to lower the cost of hydrogen through pathways such as renewables, nuclear, and thermal conversion. We discuss the opportunities to simultaneously pursue these pathways in a Houston-based hydrogen demonstration project.

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[13]See, Carbon Capture, Utilization and Storage – Lynchpin for the Energy Transition**,** March 2021 https://www.centerforhoustonsfuture.org/s/Houston-Low-Carbon-Market-Assessment-Four-Ways-Forward-A-collaborative-research-project-with-Univers.pdf

[14] Meeting the Dual Challenge: A Roadmap to At-Scale Deployment of Carbon Capture, Use, and Storage https://dualchallenge.npc.org/

[15] *S&P Platts: A Growing Hydrogen Economy presentation 31 Mar 2020*

[16] NREL The Technical and Economic Potential of the H2@Scale Concept within the United States

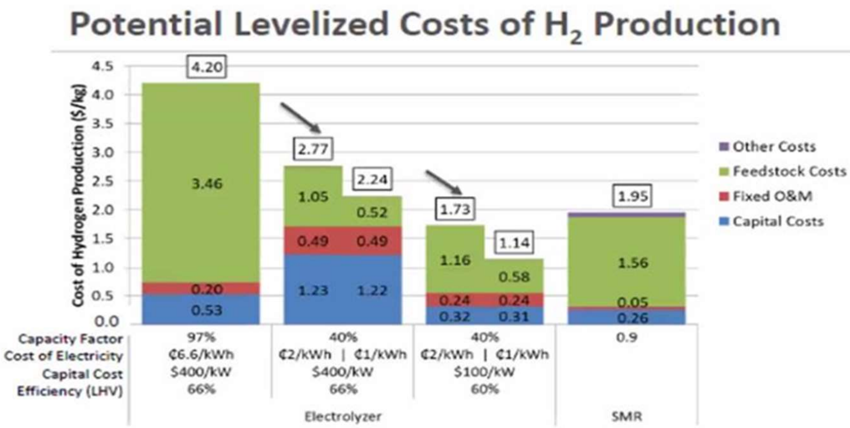
[17] Based on OSTI - Port Arthur Study and ten-year CCCUS equipment life.

[18] Assuming 1 kg of H2 produces 9 kg of $CO_2$ (Source Environmental Science & Technology 2019 53 (12), 7103-7113)

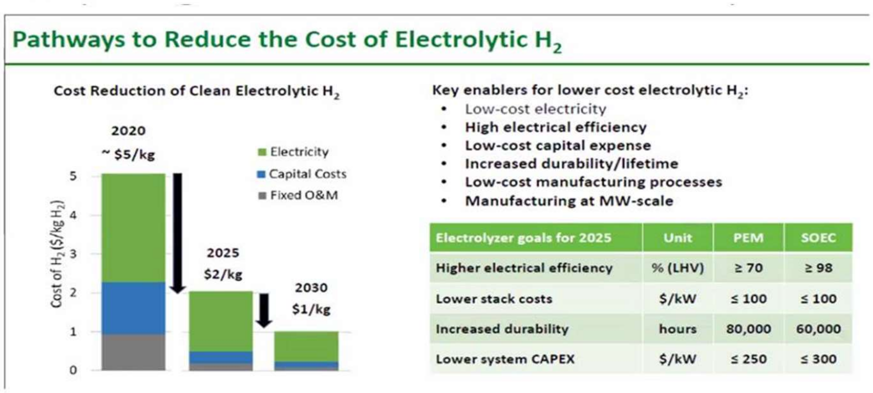
[19] Regional Carbon Capture Deployment Initiative, GPI, and Jeff Brown. 2019.

[20] A recent study by Columbia's Center for Global Energy policy has shown the advantages of this approach. Evaluating Net-Zero Industrial Hubs in the United States: A Case Study of Houston, https://www.energypolicy.columbia.edu/research/report/evaluating-net-zero-industrial-hubs-united-states-case-study-houston. A similar study in California conducted by the Energy Futures Initiative showed how an integrated carbon capture and hydrogen strategy is a key regional decarbonization strategy. See, e.g., An Action Plan for Carbon Capture and Storage in California: Opportunities, Challenges and Solutions. https://sccs.stanford.edu/events/action-plan-carbon-capture-and-storage-california-opportunities-challenges-and-solutions

Developing a green $H_2$ system: An alternative pathway to creating $H_2$ is via electrolysis, splitting a water molecule into $H_2$ and $O_2$. When electrolysis is powered with renewable energy, such as wind or solar, the $H_2$ produced is known as green $H_2$. DOE has recently specified its pathway to reducing hydrogen production costs from electrolysis as shown in the charts below:




Source: Bryan Pivovar & Josh Eichman




H2 Technologies Overview: Ned Stetson June 2021 Annual Merit Review (AMR)

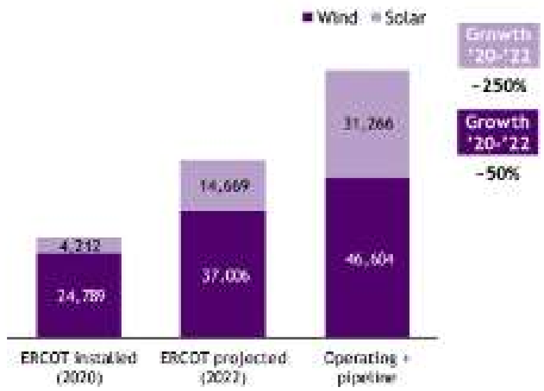
We believe the Houston region has significant advantages to incubate green H2 and accelerate the cost reduction potential of green hydrogen.

An analysis by NREL presented at DOE's recent hydrogen Annual Merit Review (AMR) shows that meeting the Earthshot goal will require a focus on lowering the capital cost of electrolysis, but also will require extremely low ($10/MWh) operational costs, which can only be achieved through extensive renewable energy deployments.

As discussed in Section 9 and 10, Houston has opportunities to drive down electrolysis costs and improve efficiency significantly due to manufacturing scale increases and technology advances. Below we focus on the ERCOT market's advantages in lowering the cost of renewables as a result of its competitive electricity market model, which is driving renewable power availability and price reductions that could spur additional green H2 at lower cost.

Texas is among the top states in the U.S. in renewable capacity and is currently No. 1 in wind power and projected No. 2 in solar power due to a 250% increase over the next five years.

The figure below shows how the capacity for solar and wind will increase from 24,789 MW and 4,212 MW, respectively, to 31,266 MW and 46,604 MW by the end of 2022.




An important advantage, given the significant power consumption requirements for electrolysis, is that the ERCOT power market includes many hours of low-priced power due to a generation mix heavy in wind power.

Low power prices create an advantage, given the high-power consumption required to produce H2 via electrolysis. The figure below shows the effects of this extensive renewable power base on creating a number of very low-price power hours.

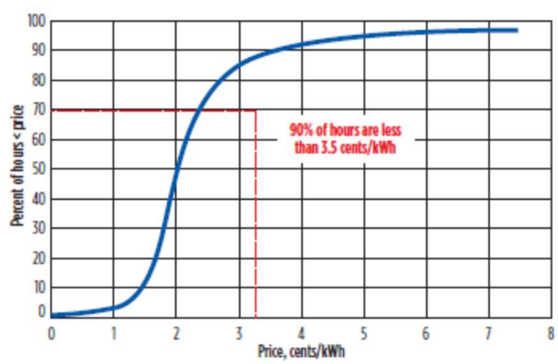



**FIG. 7.** Houston wholesale power price duration curve. Source: ERCOT.

This combination of ERCOT's low renewables prices and the opportunity to build electrolyzers at scale and reduce their capital cost (as will be discussed) makes Houston a prime location for a hydrogen production demonstration project.

**Biomass Production**: In addition, the region could utilize its vast biomass resources (Figure E-6) and develop anaerobic digesters for renewable gas production. Such projects will have **negative**

**carbon intensity** and can achieve green status despite controlled emissions from steam methane reforming. [21]

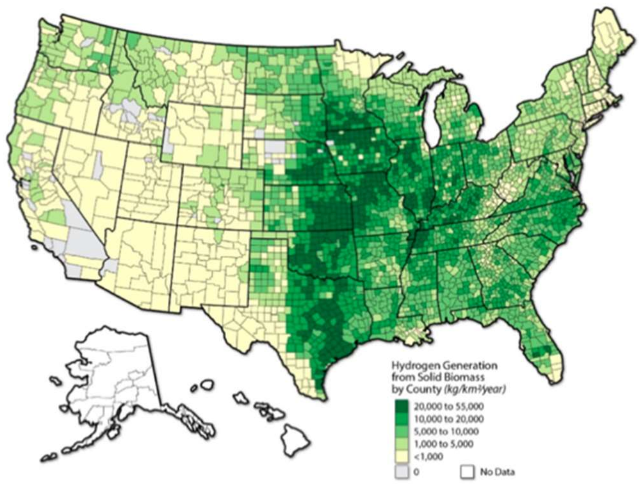



**Figure E-6. Hydrogen production potential from solid biomass resources, by county land area**

Source: Connelly et al. (2020)

There are multiple federal and state-level incentives (RFS, LCFS, RECs, etc.) that make biogas a great alternative to natural gas, even though the current non-subsidized biogas is more expensive than conventional natural gas. For instance, the 2019 average Henry Hub spot price of fossil natural gas was $2.57 per MMBtu ($3.17 in 2018 and $2.99 in 2017)[22] while biogas prices can range from $7 per million Btu (very large-scale) to $25 per MMBtu (small-scale).[23] However, the carbon intensity of dairy biogas can be as low as -400 gCO2e/MJ which translates to $96/MMBtu revenue from LCFS credits.[24]

**Turquoise Hydrogen:** Hydrogen can also be produced from pyrolysis, which is the thermal decomposition of methane to co-produce value-added carbon. Rice University's Carbon Hub is a major research initiative focused on carbon utilization, which offers an alternative to capture and storage especially in global locations where CO2 storage is not possible. Many companies in the Houston region, such as Shell, are exploring this technology.

### Implications for Developing Houston's Hydrogen Hub

By combining all of these production technologies, there is a clear opportunity for the Houston region to emerge as a leading global $H_2$ hub. As we have discussed, in the short term, this

[21] https://www.nrel.gov/docs/fy21osti/77610.pdf; BIOGAS: https://www.nrel.gov/docs/fy20osti/77198.pdf

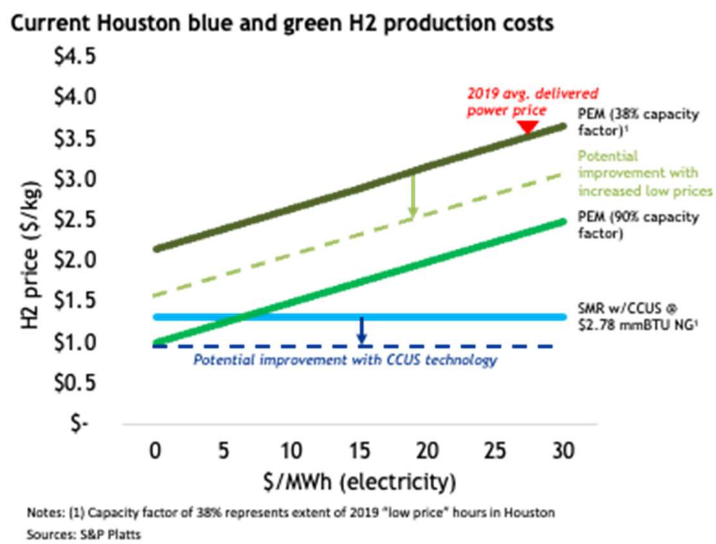
[22] U.S. EIA. Natural Gas. April 2020. Henry Hub Natural Gas Spot Price. https://www.eia.gov/dnav/ng/hist/rngwhhdm.htm. Accessed April 30, 2020

[23] U.S. EPA. September 2016. Evaluating the Air Quality, Climate & Economic Impacts of Biogas Management Technologies. EPA/600/R-16/099. https://nepis.epa.gov/Exe/ZyPDF.cgi/P100QCXZ.PDF?Dockey=P100QCXZ.PDF

[24] https://ww2.arb.ca.gov/resources/documents/lcfs-pathway-certified-carbon-intensities

would occur by accelerating decarbonization efforts for SMR plants while other production chains including biomass, pyrolysis and green H2 value chains are developed.

Our research (see figure below) as well as reports from the International Energy Agency[25] suggest that SMR w/CCUS is the most economical alternative for hydrogen production, but that other technologies could evolve quickly in a Houston demonstration project as the decline in capital costs is combined with low electricity prices available in the ERCOT market.




This picture shows how the Department, by focusing on a multi-prong demonstration project approach will help to achieve DOE's 10-year Earthshot goal.

**Developing a Long-Term Hydrogen Hub Vision**

Our long-term vision incorporates creating substantial new demand for clean $H_2$ in the near future that will drive the development of new opportunities to lower the cost of clean hydrogen production.

This presents a unique long-term opportunity for Houston region. Leveraging its world class $H_2$ infrastructure, personnel and corporate assets, Houston can globalize its $H_2$ leadership and emerge as a leading global $H_2$ hub, driving lower emissions and bridging between old and new energy systems as a path to continue energy leadership, economic expansion and job growth.

We have examined other global models, such as Rotterdam in the Netherlands and Humber in the UK (see Figure below), which have developed similar decarbonization strategies. These models show how Houston might combine existing assets (current hydrogen production with

[25] (Appendix: IEA)

carbon capture), electrolysis, and new applications to create a low-carbon hydrogen hub. We believe Houston is well positioned to achieve a similar vision.

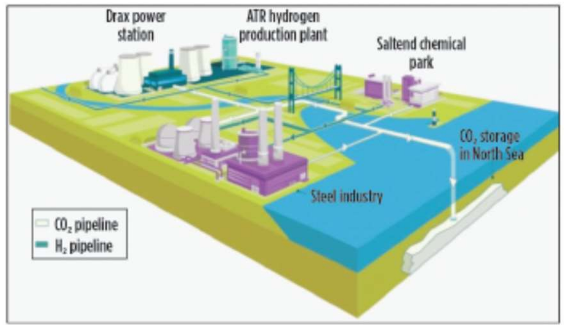



FIG. 12. Schematic of Humber, UK industrial area. Source: Equinor.

Columbia University's recently released study of Houston's assets confirmed this conclusion. That study examined international models and suggested that a competitive federal granting program on the order of $1.5–$2.5 billion of government funding could attract the private capital needed for the development of a net-zero hub. To accelerate investment and reduce risk of failure, the report suggested the program be paired with market-aligning incentives such as a hydrogen production tax credit or augmented 45Q.[26]

**1.C Is their large-scale hydrogen storage available such as geological storage, salt caverns, depleted oilfields, pipelines, or other appropriate options for hydrogen storage? If so, at what volumes?**

The Texas Gulf Coast has significant existing and future opportunities for geological storage of hydrogen, given the presence and well-developed characterization of domal salt formations. .

The Texas Gulf Coast has three of the nation's six subsurface hydrogen storage locations in salt caverns. There is large-scale hydrogen storage available in these underground salt caverns. Each is discussed below:

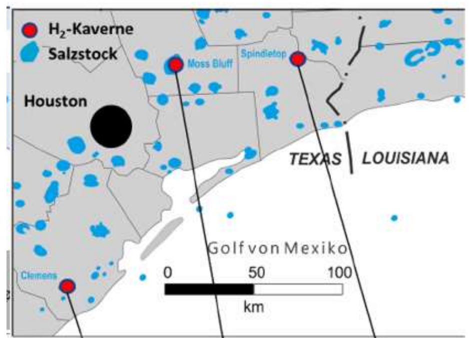
- Moss Bluff: Praxair has been storing hydrogen underground hydrogen in a salt cavern for several years to allow "peak shaving" of its hydrogen production. This facility is connected to the Praxair Gulf Coast hydrogen pipeline network, which serves the petrochemical needs of Texas and Louisiana.

- Spindletop: Owned by Air Liquide, it is the largest salt cavern on the Gulf Coast. The hydrogen network will be extended by 90 miles to southeast Texas to allow more operational flexibility.

[26] See Columbia study, https://www.energypolicy.columbia.edu/research/report/evaluating-net-zero-industrial-hubs-united-states-case-study-houston

- Clemmons Dome: ConocoPhillips has stored 95% hydrogen in its Clemmons salt dome since the 1980s. The cavern roof is about 850 m underground. The cavern is a cylinder with a diameter of 49 m, a height of 300 m, and a usable hydrogen capacity of 30 million m3, or 2520 metric tons. This storage is directly connected to the Old Ocean refinery.

Each of these companies have large hydrogen pipeline networks. More information on these facilities is in the chart below:




| Clemens Dome (ConocoPhillips) | Moss Bluff (Praxair) | Spindletop (Air Liquide) |
|---|---|---|
| 1983 | 2007 | 2014 |
| 580 000 | 566 000 | 906 000 |

In addition, depleted oil and gas reservoirs and bedded salt formations offer other potential opportunities for subsurface storage. However, these types of hydrogen storage have not yet been used for storing hydrogen.

### D) Are there existing hydrogen refueling stations or liquefaction plants in the region, or plans underway for such infrastructure?

The development of refueling and liquefaction infrastructure is a work in progress. Liquefaction plants are being developed in the Houston region. In 2021, Air Products' newest liquid hydrogen plant at its La Porte, Texas industrial gas facility is scheduled to go online. Plans to build the plant were first announced in 2018. Once online, the liquid hydrogen plant will produce approximately 30 tons of liquid hydrogen per day. It will draw its hydrogen from Air Products' existing Gulf Coast hydrogen pipeline system network.[27] Praxair also has a similar project expected to come online in 2021.

[27] https://www.h2-view.com/story/made-in-america-new-liquid-hydrogen-plant-and-extensive-pipeline-network-position-air-products-for-growing-hydrogen-demand/

There have also been other recent project announcements. [28]

In addition, the Texas Gulf Coast region has the most extensive LNG facilities in the country and modifying existing LNG infrastructure to liquefy hydrogen would be 50-60% cheaper than building infrastructure for hydrogen. [29]

**E. Describe any environmental or ecological impact, both positive and negative (e.g., are there any wetlands, NEPA issues, environmental justice communities, other considerations).**

**F. Is the region a brownfield or greenfield site?**

**G. What siting concerns, if any, need to be addressed? Would any mitigation plans be required (e.g., flood plain or other siting challenges such as hydrogen coupled with offshore wind)?**

As to the three questions above, the Center has not undertaken a study of any particular site to determine the environmental and ecological impacts of a specific project.

[28] https://www.prnewswire.com/news-releases/joule-processing-brings-ultra-energy-efficient-hydrogen-liquefaction-plant-to-market-301293880.html
[29] https://www.naturalgasintel.com/lng-infrastructure-easily-modified-to-liquefy-hydrogen-says-chart-ceo/

## End Users for Hydrogen in the Region and Value Proposition

**2. Please describe existing and potential future end users for the hydrogen in the region, such as industrial, transportation, chemicals manufacturing, heavy-duty trucks, and other end uses.**

***2.A Distinguish between existing and potential future end users and specify anticipated time frame*.**

**Existing use cases:**

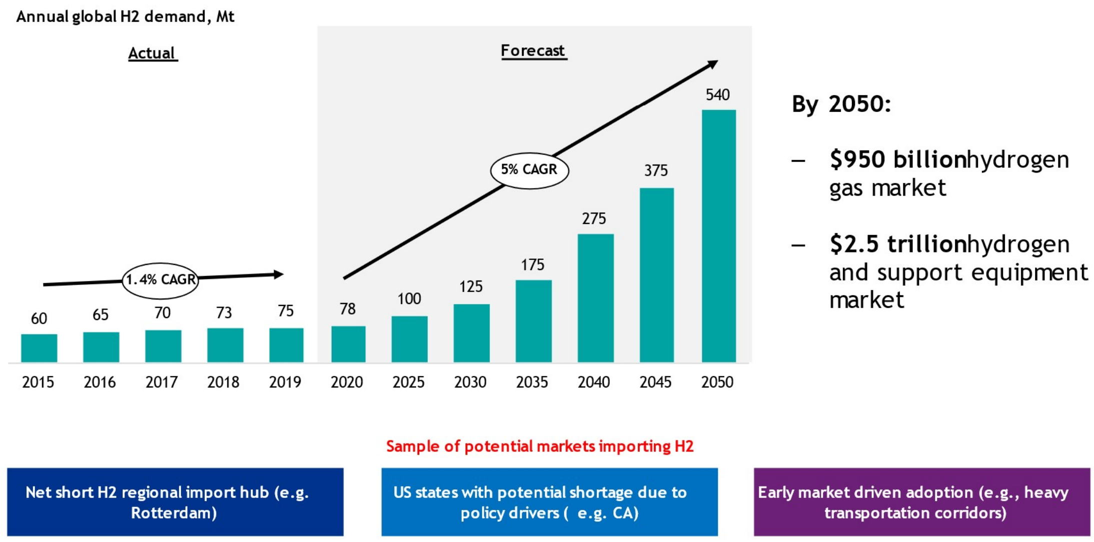
**Petroleum applications:** Hydrogen today is dominated by industry applications in oil refining. Currently, U.S. oil refining consumes about 10 MMT of hydrogen annually, making it the largest hydrogen market. The total captive and merchant hydrogen demand (other than reformer-byproduct hydrogen) of U.S. refineries is projected to increase by 27% between 2017 and 2050, from 5.9 to 7.5 MMT/yr.

This projected growth is primarily due to an increase in the estimated diesel-to-gasoline ratio as well as processing of lower-quality crude (lower API gravity and higher sulfur), which require higher hydrogen use.

**Future demand for hydrogen:**

According to the Hydrogen Council, global demand for hydrogen is expected to increase to almost $1 billion in gas and $2.5 trillion in associated equipment by 2050. Below, we will discuss market applications for H2 beyond its existing primary uses in oil refining and as petrochemical feedstock and that can be expected to drive this demand.

## A Global demand for H2 is increasing sharply, and some regions will need to import H2 to meet their demand




Source: Barclays, HSBC, Hydrogen Council

**Future Applications for Hydrogen in the Houston Region**

Over the last year, the Center has concluded a preliminary assessment of the potential future applications for hydrogen in the Texas Gulf Coast region. A summary of markets we examined is below:

**Transportation:** The Center's research concluded heavy trucking should be an initial priority to investigate.

- Limited new infrastructure requirements: Trucking requires limited new infrastructure to use H2 as a fuel, and H2 fuel competes with relatively expensive and relatively higher-emitting diesel fuel.
- Advantages over Battery Electric Vehicles (BEVs): The advantages of H2 fuel cell power in this application are many: low weight, fast refueling, high range and relatively low new infrastructure costs. Additionally, the speed of refueling, as well as range and torque requirements, favor H2 over batteries for heavy trucking.
- Lower Emissions than Diesel: The Center's research also showed emissions still would be lower than diesel, even if the H2 fuel was gray H2. As gray H2 is paired with CCUS to create blue H2, the emissions benefit of using H2 fuel increases. Our economic modeling showed that heavy trucking is particularly attractive as an initial new market when compared to existing diesel trucks in several specific Texas trucking corridors.
- Existing corridors: Several high-concentration trucking markets involve Houston and its port

areas, Dallas (a regional distribution hub) and San Antonio (which ties into shipping from Mexico). Tapping high-density corridors minimizes the infrastructure required to achieve meaningful scale regionally, improving the economics of market entry and expansion.

**Industrial applications:** Given its industrial manufacturing facilities and hydrogen production, the Texas Gulf Coast is well positioned to become a hydrogen hub and to attract new industries such as decarbonized steel.

As shown on the chart below, we see new industrial applications emerging as hydrogen migrates from feedstocks to fuels and new integrated processes: While hydrogen is used primarily today as a feedstock in oil refining and chemicals manufacturing, it is expected to have applications as a zero- or low-carbon industrial fuel or as an input for integrated manufacturing processes, such as steel manufacturing. Initially, we see hydrogen as a drop-in fuel replacement for coal or natural gas in some applications (ex: aluminum or glass). Bigger opportunities in cement and steel will require a manufacturing process redesign and take time.

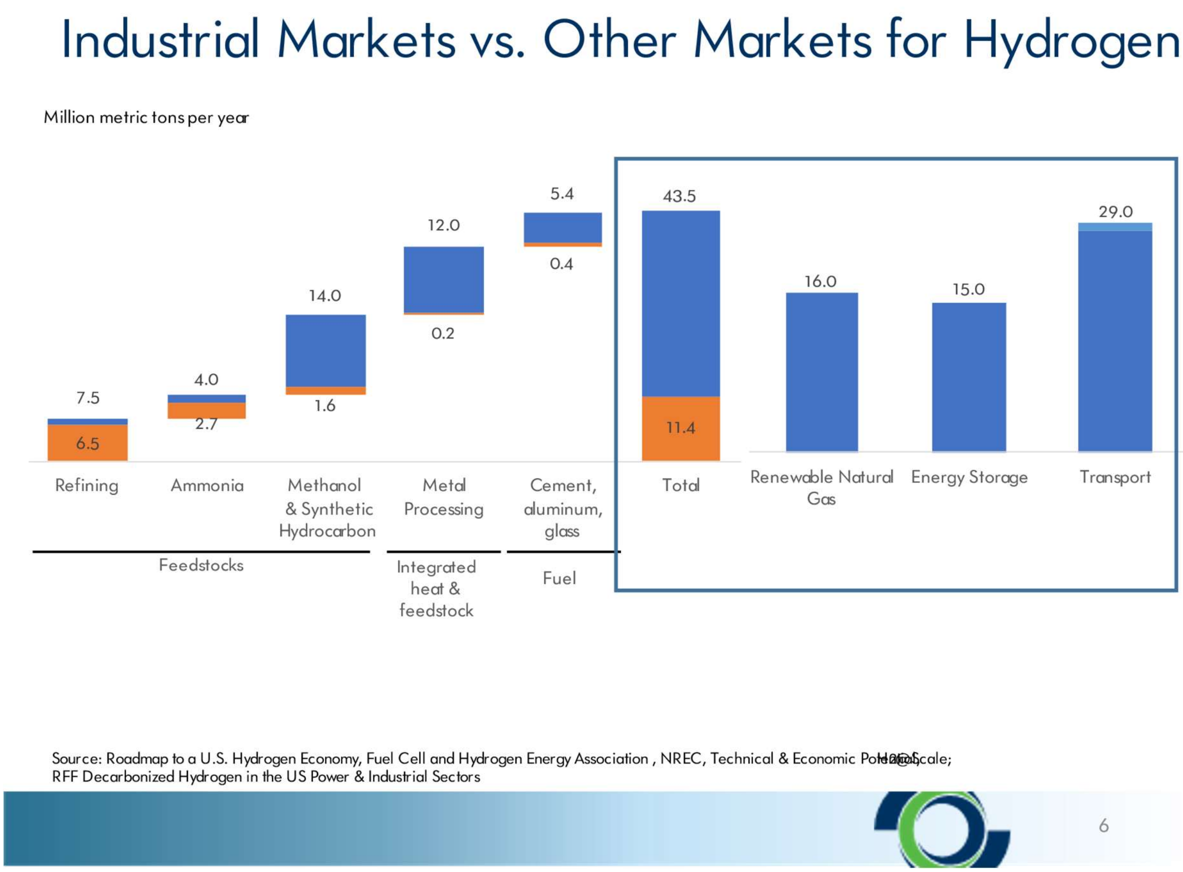
## Hydrogen's Role in Industrial Decarbonization Strategies

| Target | Type | Decarbonation Strategies | Rationale |
|---|---|---|---|
| Fuel (e.g. industrial high temperature heat application ) | Cement | Hydrogen or CCUS | • Hydrogen could substitute for fossil fuels to reduce heat emissions<br>• CCUS could capture post combustion emissions |
| | Aluminum | Use hydrogen for aluminum recycling | • Substitute hydrogen for natural gas on recycling operations |
| | Glass | Use hydrogen as a fuel for glassmaking | • Substitute hydrogen for natural gas on recycling operations |
| Integrated Heat and Feedstocks (e.g. Steel and Iron Production) | Blast Furnace – Basic Oxygen Furnace | Hydrogen inappropriate given the role of coal in the process | • N/A |
| | Direct Reduction/Arc Furnace | Green or Blue Hydrogen | • Decarbonized hydrogen can reduce emissions from natural gas or coal |
| Feedstocks: Oil and Chemical Production | Oil Refining | Blue (SMR + CCUS) or Green | • Decarbonize existing oil refining processes |
| | Ammonia Production | Blue (SMR + CCUS) or Green | • Substitute low carbon hydrogen for gray hydrogen |
| | Methanol Production | Low benefit | • Emissions are retained during the production process |
| | Synthetic Methane | Hydrocarbon methanol to gasoline | • React hydrogen & CO2 |

Source: Roadmap to a U.S. Hydrogen Economy, Fuel Cell and Hydrogen Energy Association , NREC, Technical & Economic Potential; H2@Scale; RFF Decarbonized Hydrogen in the US Power & Industrial Sectors

4

Nevertheless, there will be significant future industrial applications for hydrogen. The potential available industrial market for hydrogen is over three times the current industrial market and will likely exceed the potential market for energy storage, renewable natural gas and transportation.




Below we discuss specific opportunities to develop new applications for industrial uses for hydrogen.

- **Steel Production:** The Texas Gulf Coast could be the demonstration site for the development of a U.S. low-carbon steel industry by leveraging existing steel production facilities.

  Texas is already home to one of the world's most advanced direct reduction plants. Direct reduction of iron (DRI) uses natural gas, synthesis gas, and/or hydrogen to decrease the energy use and emissions of steel production while improving steel quality compared with blast furnace/coke oven technology.

  The DRI process can use mixtures of hydrogen and carbon monoxide or natural gas up to 100% hydrogen. Mixtures may be favorable as they may reduce the operating cost (by mixing hydrogen with lower-cost natural gas) and because the presence of carbon monoxide can improve the quality of some steel products. Experts suggest a 30% mix of hydrogen with natural gas (by energy) is feasible without altering the production process.

The Corpus Christi DRI plant, owned by Austria's Voestalpine Group, is the world's most advanced direct reduction plant, producing high-quality pre-materials used in steel production. It currently uses natural gas to produce two million tons of hot briquetted iron each year. The company has indicated it has plans to work to gradually decarbonize steel production, first by the partial substitution of coal and coke with gas-based bridging technologies, and then with the long-term, gradual use of CO2-neutral hydrogen.[30]

- **Cement:** Both CCUS and hydrogen could be applied to cement production to achieve deep reductions in cement emissions.[31] With appropriate equipment modifications, decarbonized hydrogen could substitute for fossil fuels to reduce the heating emissions in cement production. BNEF (2020) finds that zero-carbon hydrogen at a delivered price of $1.00/kgH2 would be a cost- effective source of heat for cement production if there were a carbon price of $60. Because most cement emissions are from process CO2 rather than heating, CCUS would appear a more effective option than fuel switching to hydrogen. However, although CO2 from calcination is almost pure (allowing for low-cost carbon capture), the concentration of CO2 in combustion gases is low (increasing the cost of carbon capture), thereby reducing the efficiency of applying CCUS to the combined stream of process and flue gases. Technology under development to separate the process gases from the combustion gases would enable low-cost CCUS for calcination and a low-carbon fuel, like hydrogen, for combustion (Project LEILAC 2020).

  In early 2021, CEMEX introduced hydrogen as a part of the fuel mix in all cement facilities in Europe. The company is planning to invest $40 million to extend this technology to the US and the rest of the world.[32] Cemex, whose North American headquarters is in Houston, has three cement terminals in Houston region as well as production facility in San Antonio. It is likely that Cemex will become a potential off taker of hydrogen in the region, to meet the company's net-zero targets.

- A**mmonia:** The entire Gulf Coast region produces a significant amount of U.S. ammonia production due to low natural gas costs. Ammonia presents both an industrial decarbonization opportunity as well as a potential export opportunity since ammonia is easier to transport than hydrogen.

  In 2020, total U.S. ammonia production in the U.S. was estimated at ~ 14 million metric tons produced from 16 companies at 35 facilities with the majority of the U.S. production capacity in Louisiana, Oklahoma, and Texas.

[30] https://www.voestalpine.com/stahl/en/Stories/Construction-of-the-HBI-plant-in-Corpus-Christi-progressing-at-a-brisk-pace
[31] https://media.rff.org/documents/RFF_Report_20-25_Decarbonized_Hydrogen.pdf
[32] https://www.cemex.com/-/cemex-successfully-deploys-hydrogen-based-ground-breaking-technology

Ammonia production is growing in the Houston region with the addition of a new $1-billion-plant. Gulf Coast Ammonia LLC (GCA), Air Products, and Eastman Chemical Company plan to build the world's largest single-train ammonia synthesis loop in Texas City which will produce roughly 1.3 MM tons per year (about 9% of the world's supply) when it opens in 2023.[33] Air Products is also constructing a $500 MM SMR to support the facility.

About 80 percent of ammonia is used in fertilizer production (Hydrogen Council 2020), a proportion that may increase only modestly as countries aim to limit fertilizer use or increase its efficiency, the remaining 20 percent of current ammonia demand—for other industrial applications—is expected to grow significantly, which could grow global hydrogen demand for ammonia to 44 MMt/year by 2050 (IEA 2019). [34]

As discussed in Section 3, blue hydrogen is the most promising decarbonization option for ammonia production for the near future[35] given existing SMR economics. until green hydrogen production costs decline.

- **Biofuels:** In the future, biofuels could be the primary option for applications needing energy-dense liquid fuels (e.g., aviation, marine transport) since cellulosic ethanol doesn't meet performance specifications. In addition, a large fraction of the carbon in biomass is emitted as carbon dioxide during fermentation to produce ethanol. As such, additional biofuel technologies are being developed. Many of the new technologies use hydrogen directly—for conversion, hydro processing, and/or hydrotreating of the biofuels—and all will use hydrogen indirectly through the increased need for ammonia fertilizer in biomass production.

**Export:** Many markets, domestically and globally, will need more H2 than they can produce over the next decade to meet decarbonization goals. Some markets, domestic and international, will need H2 imports to meet demand.

A strong case exists for the Gulf Coast to become a global hydrogen exporter with its world-scale, in-place H2 production capacity; low-cost natural gas feedstock; opportunity to create a low-cost, at-scale CCUS system; and global H2 storage and transport infrastructure.

For example, a promising, early blue H2 opportunity for Houston could be exporting to California to take advantage of the state's Low Carbon Fuel Standard incentive. A blue H2 system, anchored in the Gulf Coast area, could expand to become a major H2 exporter, leveraging its low cost, existing scale, and advantaged pipeline and shipping positions.

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[33] https://businessfacilities.com/2020/01/1b-ammonia-plant-coming-to-greater-houston/
[34] https://media.rff.org/documents/RFF_Report_20-25_Decarbonized_Hydrogen.pdf
[35] https://media.rff.org/documents/RFF_Report_20-25_Decarbonized_Hydrogen.pdf

Hydrogen from Houston could be exported to California as transportation fuel and generate LCFS credits. In 2020, the California Air Resources Board (CARB) approved several pathways for hydrogen with negative carbon intensity.[36]

For example, FirstElement Fuel and Air Products used *book-and-claim* accounting for biomethane to hydrogen and was able to claim the environmental attributes of dairy RNG procured in Fair Oaks, Indiana. As a result, the pathway granted -287.07 CI,[37] which is equivalent of **$11.72 per H2 kg LCFS credit**.[38] We plan to investigate whether similar pathways are available for hydrogen or biogas production in Texas.

This could be a midterm strategy to accelerate, at scale, volumes of clean H2 to domestic and global markets.

We are also investigation whether initial export markets may include domestic trucking markets beyond California and international markets, such as the Netherlands, Germany or Japan, which have regional supply projections short of demand requirements.

**Power generation/Energy storage:** Hydrogen is one of the leading options for storing renewable energy, and hydrogen and ammonia can be used in gas turbines to increase power system flexibility.

As will be discussed in response to Question 4, the Houston region could be an early adopter of hydrogen-based energy storage. Center's research concluded the region has all the ingredients to lead in using hydrogen to more the power grid more reliable.

**Shipping and aviation:** These sectors have limited low-carbon fuel options available and represent a significant opportunity for hydrogen-based fuels.

- **Shipping:** Energy density issues preclude using batteries in shipping, which requires energy dense liquids or compressed gaseous fuels that allow for retrofits/current hull designs. Future shipping may be achieved with methanol, ammonia or hydrogen, but hull design will need to be changed significantly.

  Substantial cargo carrying capacity is sacrificed for energy storage in a retrofit, and new builds would require significant redesigning. Also, a lack of infrastructure at ports is another barrier to the uptake of hydrogen. The solution to the growth in this sector is constructing hydrogen infrastructure at specific point-to-point routes between highly developed ports.

[36] https://ww3.arb.ca.gov/sites/default/files/classic/fuels/lcfs/fuelpathways/current-pathways_all.xlsx
[37] https://ww2.arb.ca.gov/sites/default/files/classic/fuels/lcfs/fuelpathways/comments/tier2/b0145_summary.pdf
[38] Assuming LCFS credit price of $190 and gasoline CI standard of 90.74 gCO2e/MJ

- **Aviation** emits roughly 2% of global emissions or 900 Mt $CO_2e$ p.a. Hydrogen is increasingly considered as one of the most promising decarbonization technologies for future aircraft. However, despite the fact that hydrogen has an energy-density-per-unit mass that is three times higher than traditional jet fuel, a variety of challenges must be addressed before widespread adoption can happen.

  The aviation sector is uniquely dependent on gas-turbine engines and jet fuel for propulsion. Using batteries to power aircraft for short/medium and long-haul flights is impractical given the current state-of-the-art of battery technology.

  All-electric aircraft are being developed and show potential for short-range flights. The use of cryogenic hydrogen is in the research and development process, but similar to aircraft electrification is not expected to be viable commercially until later in the century.

  For hydrogen to really achieve widespread adoption across the aviation industry, it must be available at airports worldwide. Advancement in this area is in its infancy.

  Regulations and aircraft design means commercial aviation is dependent on drop-in jet fuels for the foreseeable future, with power-to-liquid fuels being deemed the most suitable option due to the scale required. Fuel costs and a lack of refueling infrastructure are key barriers facing alternatives. Policy and financial incentives are needed to encourage the uptake of low-carbon fuels.

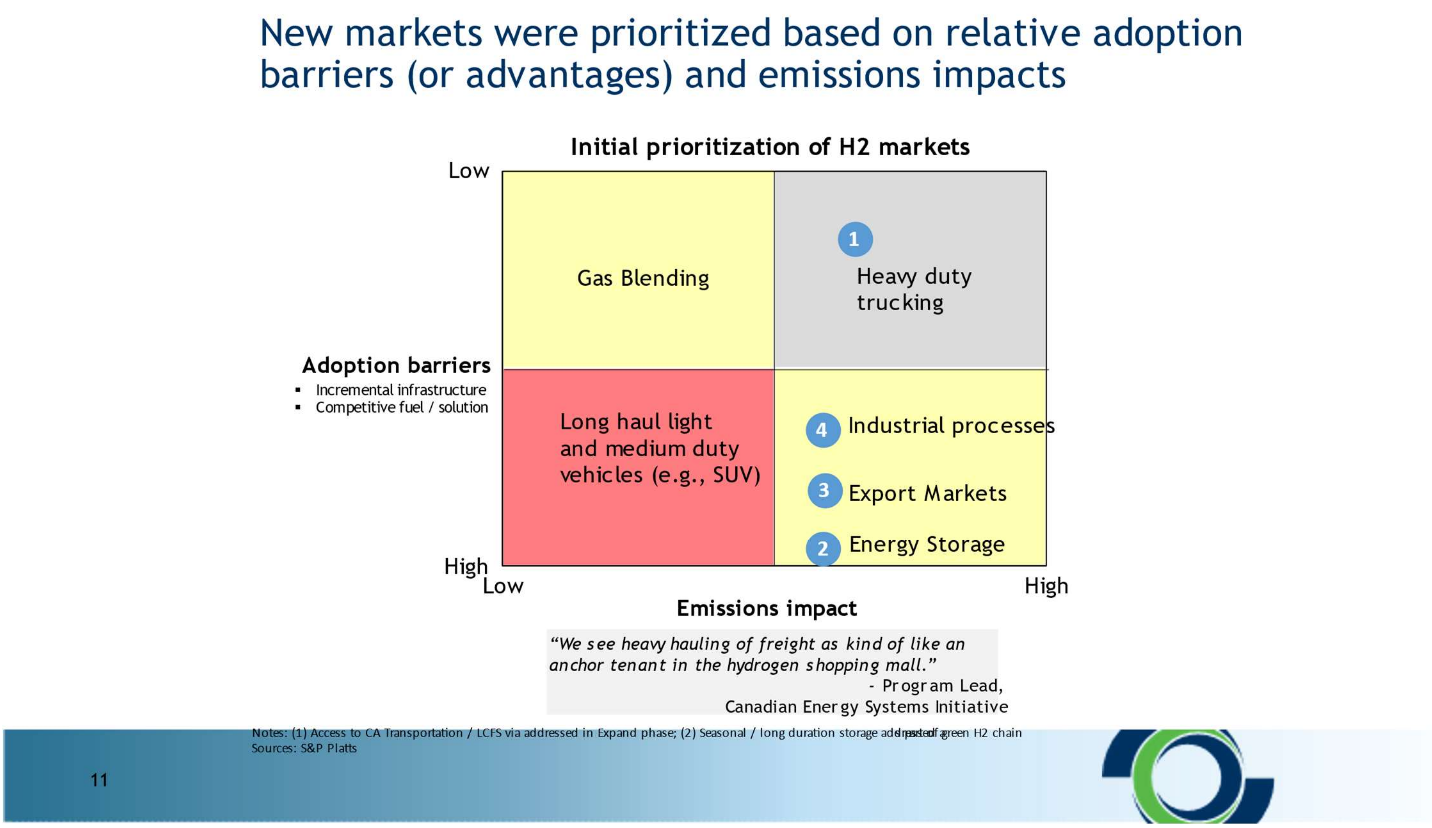
  One main challenge is developing the large-scale transport and infrastructure solutions required to supply airports with the amount of hydrogen needed to fuel aircraft.

  A recent IEA study suggests repurposing existing infrastructure, including the millions of kilometers of pipelines used to move natural gas could be a cost-effective solution. Larger quantities of hydrogen could be shipped by pipeline from production sites, while smaller quantities could be moved by truck. In addition, some airport locations could develop infrastructure for on-site hydrogen production, particularly if a renewable energy supply is close.

**Ongoing Work on Future Applications for Hydrogen in the Houston Region**

As discussed above, the Center's research has shown that there are new H2 market opportunities in the Houston region. The 2x2 matrix below represents our attempt to prioritize these opportunities.

As a result of this analysis, the Center is currently focused on projects that look at the potential for new applications for hydrogen in the Houston region in transportation, export markets and energy storage since these are the applications that fit best with Houston's capabilities and have the highest near-term potential.  In the future, we expect to examine applications for high temperate industrial processes, shipping and aviation.




***2.B Specify the amount of hydrogen currently needed and potential future needs (tonnes per day and per year)*.**

As part of its work to understand Houston's opportunity as a low-cost, low-carbon hydrogen hub, the Center has leveraged research in the National Renewable Energy Lab's report on the Technical and Economic Potential of the H2@Scale Concept within the United States. [39]

In that report, NREL created three measures for potential applications of hydrogen: total consumption potential (amount consumed if no competing products), serviceable consumption potential (amount consumed if there are competing products assuming a zero price) and the economic consumption potential (the amount consumed at various prices).

NREL's work looked at the demand for hydrogen across various applications and on a county-by-county basis. We were able to obtain NREL's county level estimates and therefore could determine Houston's (and the state of Texas') position as a potential hydrogen demand center based on serviceable consumption potential.

The chart below shows that the Houston MSA is expected to account for 4.1% of serviceable consumption, the Texas Gulf Coast represents 5.8% and the state of Texas represents 11.5%.

| Area | Refineries ton/year | Metals ton/year ** | Ammonia ton/year | Biofuels ton/year | Synfuels ton/year | Natural Gas ton/year | Energy Storage ton/year | Metal Industry ton/year[40] | Light and Medium Heavy Duty fcev ton/year | Total per Region ton/year |
|---|---|---|---|---|---|---|---|---|---|---|
| **Houston MSA*** | 1,062,346 | 200,000 | 244,449 | 259,164 | 854,167 | 34,902 | 728,206 | 510,000 | 517,285 | **4,410,519** |
| **Gulf Coast + Southeast** | 1,690,805 | 200,000 | 289,279 | 424,086 | 1,354,167 | 108,585 | 891,761 | 510,000 | 672,567 | **6,141,250** |
| **All Texas** | 2,330,759 | 200,000 | 466,906 | 1,013,095 | 1,958,333 | 985,024 | 2,017,197 | 510,000 | 2,818,557 | **12,299,871** |

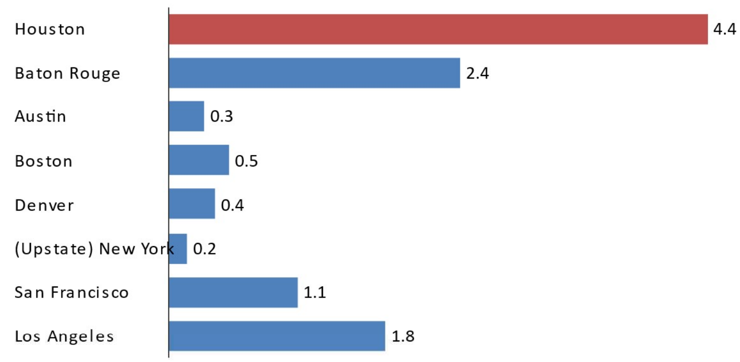
*Houston MSA: Metropolitan area of Houston encompasses nine counties in Southeast Texas (Austin, Brazoria, Chambers, Fort Bend, Galveston, Harris, Liberty, Montgomery and Waller)

In addition, we used the NREL data to look at how Houston compares to other regions. This shows NREL expects Houston to have the highest potential demand among peer cities.

[39] https://www.nrel.gov/news/program/2020/study-shows-abundant-opportunities-for-hydrogen-in-a-future-integrated-energy-system.html

Houston has the highest demand potential among peers

**Estimated clean hydrogen market demand in select US metropolitan areas[1],**
mtpa H2




- Based on NREL H2@Scale estimates; maritime demand included based on potential global demand of 100 mtpa ammonia as bunker fuel with Houston (3%) and LA ports (1%) and Baton Rouge, Boston, San Francisco assumed to be 0.1%
- Note: Metropolitan areas include the following counties/parishes:
- Houston: Austin, Brazoria, Chambers, Fort Bend, Galveston, Harris, Liberty, Montgomery, Waller
- Baton Rouge: Ascension, Assumption, East Baton Rouge, East Feliciana, Iberville, Livingston, Pointe Coupee, St. Helena, West Baton Rouge, West Feliciana
- Austin: Bastrop, Caldwell, Hays, Travis, Williamson
- Boston: Norfolk, Plymouth, Suffolk, Essex, Middlesex, Rockingham, Strafford
- Denver: Adams, Arapahoe, Broomfield, Clear Creek, Denver, Douglas, Elbert, Gilpin, Jefferson, Park
- (Upstate) New York: Albany, Rensselaer, Saratoga, Schenectady, Schoharie
- San Francisco: Alameda, Contra Costa, San Francisco, San Mateo, Marin
- Los Angeles: Orange, Los Angeles

Source: NREL

CENTER FOR HOUSTON'S FUTURE

### *2.C Specify the proposed distribution network and geographical footprint required to reach end users.*

As discussed above, the Houston region has an extensive network of hydrogen pipelines serving the existing refining and petrochemical industry. This network could clearly serve new industrial hydrogen users along the ship channel.

In addition, it could anchor part of a transportation distribution network that would serve heavy and medium duty trucks in the region. Our initial analysis shows that this could be done at relatively low costs and would significantly reduce the break-even economics for heavy duty transportation. The Center is investigating both these infrastructure investments and the potential for leveraging them into a broader distribution network that would rely on tube trailers and would serve the other parts of the Houston region.

### *2.D Are there any commitments already in place for off-takers or by when could there be commitments?*

The Center is currently conducting a survey to identify the companies that are most likely to commit to off-take agreements for emerging uses of hydrogen.

***2.E If using existing transport infrastructure are there limitations to the amount of hydrogen that can be blended into these systems and/or will there be modifications to these systems necessary to carry hydrogen?***

The Center to date has not undertaken a study addressing this topic.

## 3. Please describe the business case, including the return on investment and timeframe.

***3.A Include the costs for all stages of hydrogen use, including production, storage, delivery, infrastructure, and end use.***
***3.B What are the anticipated capital and operational costs?***

To date, the Center's work has focused on examining the business case for hydrogen applications primarily in heavy duty transportation and has focused on several pilot opportunities for heavy duty (Class 8) hydrogen trucks.

Our economic analysis focused primarily on examining the cost of fuel cell electric vehicles (FCEVs) powered by hydrogen compared to diesel trucks. We concluded that FCEVs would have comparable or lower total cost of ownership than diesel within five years.

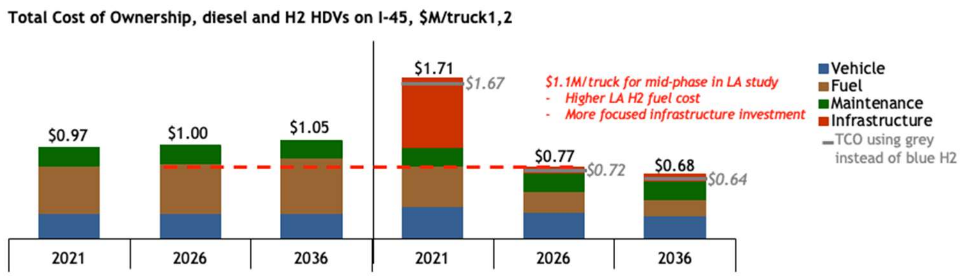
We have several high-concentration trucking markets involving the Houston area (I-10, I-45 and regional chemical trucking in/around the Houston ship channel). This minimizes the infrastructure needed to achieve meaningful scale regionally, improving the economics of entry and expansion.

To begin this analysis, we picked two routes: *Dallas to Houston* (DTX to HTX) and *Houston to San Antonio* (HTX to SA) as the most viable options. The results of this economic analysis are as follows:

**Economic Comparison: H2 vs Diesel**

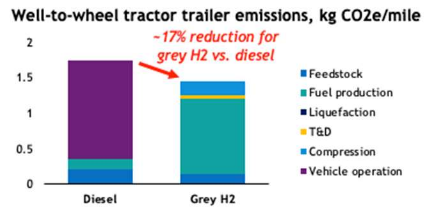
The figure below illustrates the potential economics of the I-45 corridor, where a Department of Transportation funded planning study is underway by the North Texas Council of Governments (NCTCOG). [41] As with analogous markets such as the Port of LA, economics are favorable for the I-45 corridor at scale.

[41] https://www.nctcog.org/trans/about/committees/ih-45-zero-emission-vehicle-corridor




Phased Market growth for converting diesel to H2[1]

| Category | Pilot | Expand | Rollout |
|---|---|---|---|
| Year | 2021 | 2026 | 2036 |
| Trucks | 10 | 121 | 1,205 |
| Corridor converted (%) | n/a | 2.5 | 25 |
| Filling Stations | 2 | 3 | 14 |




Coupling this potential with the fact that companies such as Nikola, Toyota and Hyundai are developing and piloting the manufacture of H2 trucks, and shippers are increasingly seeking to curb emissions, we are optimistic this could be an early new H2 market in Texas.

Adoption of hydrogen as a fuel in the Port of LA and other areas has been catalyzed by incentives for updating truck fleets for lower-emission fuels and for building infrastructure. Incentive requirements would be less here, given the region's current hydrogen production and dense heavy-trucking patterns.

*Hydrogen Delivery Cost:*

Assuming the use of a **tube trailer** delivery system, we estimate initial hydrogen delivery will cost **$0.27/kg (HTX to SA) and $0.32/kg (DTX to HTX)**.[42] We also reviewed the **pipeline** delivery system but given the high capital expenditures and relatively low volume of hydrogen at the initial stage, a dedicated pipeline system does not seem economically viable.

*End Use Infrastructure and On-site Storage Cost:*

Utilizing the *HDRSAM Model from Argonne National Lab*, we estimated the initial fueling station cost for 10 hydrogen trucks (Activate Phase) will be $ 3.25M (HTX to SA) and $ 3.35M (DTX to HTX).[43] This can be converted to **$11.66/kg** (HTX to SA) and **$9.60/kg** (DTX to HTX). However, as projects scale and additional trucks come online (Rollout Phase), the station cost will drop to **$1.23/kg** (HTX to SA) and **$1.05/kg** (DTX to HTX). [44]

[42] $1.32 per mile delivery cost NREL: Hydrogen Pathways Well to Wheel; converted from 2007$ to 2020$ considering 2% inflation per year until 2020
[43] ANL: HDRSAM Model; based on 3 HDV/station, 1 dispenser, 700 bar cascade dispensing, low production volume (converted to 2020$)
[44] See Appendix: Key Cost Assumptions

We are currently engaged in follow-up work to build a team of companies and stakeholders that would be willing to move forward with planning for a heavy-duty trucking pilot.

As part of a demonstration project application, we would provide additional information on the specific network design for a hydrogen delivery network and identify the parties interested in participating.

### *3.C What local or regional policies or regulations, if available, would support the business case?*

Texas has an existing diesel truck replacement program called the Texas Emissions Reduction Program (TERP) that provides significant funding for diesel truck replacements.

The program is funded by vehicle and other fees and brings in about $270 million a year. The program provides some funds for building hydrogen infrastructure, but the amounts are currently capped at $600,000 per project. In addition, the program is not currently structured to incentivize the development of innovative new pilots since most of those fleet owners who might participate in such a program would have already replaced their older diesel trucks.

Nevertheless, the program represents a significant investment by the state and there is work underway to modify the program so that it is a better fit for the types of heavy-duty transportation projects suggested here.

## 4. What is the potential benefit to utilizing hydrogen to enable grid resiliency?

### *4.A Are there opportunities for hydrogen storage as backup power for the energy grid in case of power outages?*

One of the compelling pathways to achieve the “1 for 1 by 1” Earthshot is via use of excess renewable electricity generated from wind and solar, in combination with low temperature electrolysis.

Indeed, the Greater Houston area could benefit from using hydrogen storage as backup power for the grid in case of outages. The importance of reliable back-up power was highlighted in the February 2021 freeze, during which insufficient generation capacity caused prolonged blackouts across Houston and the state. During the freeze, natural gas production – upon which many generators rely – also froze. Having supplies of hydrogen stored underground could have mitigated a fuel supply issue.

The Greater Houston area has opportunities for hydrogen storage as backup power because of high generation of wind and solar power, salt cavern storage, and the H2 pipeline network. Increased long duration storage will be needed as renewable power penetration increases on the grid across Houston and Texas.

The figure below shows how the need for long duration energy storage is likely to increase in the ERCOT power region. As renewable penetration increases, the need for storage duration increases. Also shown are various mediums and their suitable storage times. Batteries are viable in the short term, covering durations of 5 minutes to 2 hours.

Beyond 2 hours, batteries become less competitive vs. other technologies, such as pumped hydro, compressed air energy and hydrogen. Hydrogen is particularly suitable for very long duration storage (e.g., multi-day or seasonal storage).

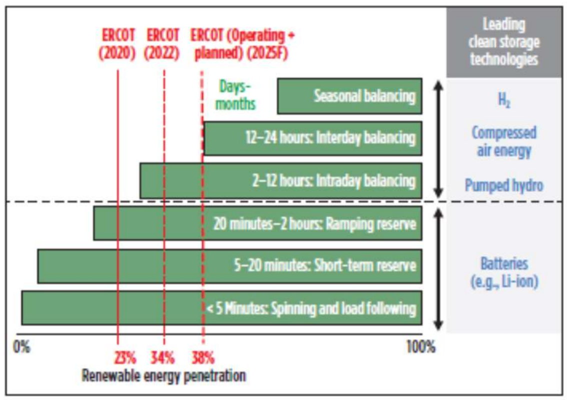



**FIG. 9.** Energy storage requirements vs. renewable energy penetration levels. Source: ERCOT.

H2 generation from renewable power is considered the preferred option for longer duration, multi-day or even seasonal storage, taking advantage of abundant salt dome options for cavern storage on the Gulf Coast, which is the lowest cost option for H2 storage. This combination of renewable power generation with longer-duration storage can solve reliability issues associated with ERCOT, while also allowing for a high extent of decarbonization.

In this manner, excess power production can be stored in the form of H2. It can then be used to provide low-cost H2 to decarbonize heavy industry or transportation or can be put back onto the grid via gas turbines or fuel cells as a means of storage.

Below we discuss how we might leverage unique assets in Houston and across ERCOT to achieve this goal.

<u>Renewables Growth</u>

The remarkable growth in renewable energy in Texas increases the opportunity to take advantage of large-scale energy storage to minimize the mismatch between energy generation and demand.

As mentioned in the response to question 1.b., Texas is the nation's top wind energy producer - accounting for about 20%[45] of the electricity generation in Texas. The state is also poised to become second in California in solar production to California, with expected solar market growth of 250%.

The figure below indicates the extent of low- cost power hours available daily in Texas. Low-cost power is a significant advantage in producing hydrogen from electrolysis. Overall, ERCOT produces power for around $30/MWh about 70% of the hours per year.

Studies show that high penetration of renewables can lower the cost of grid power which in combination with low-cost electrolyzers can provide for low-cost hydrogen even at capacity factors as low as 10-15%.[46]

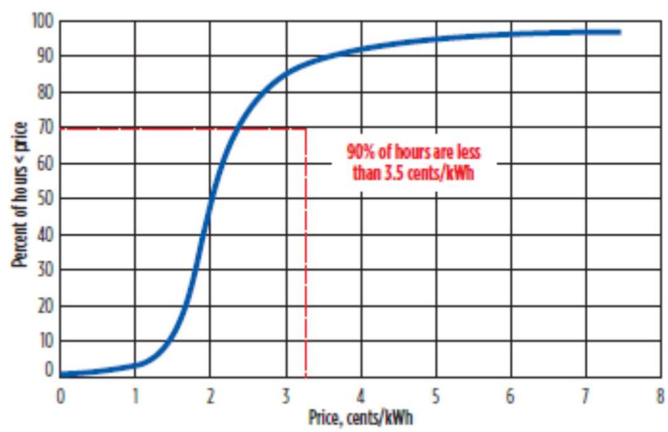


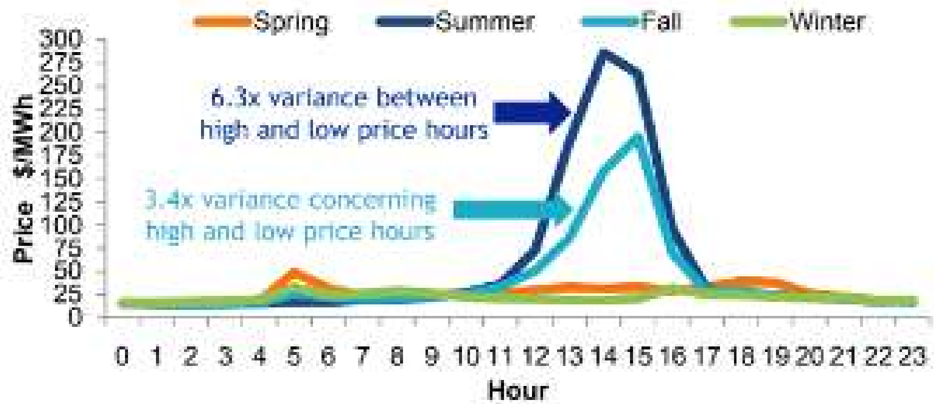

**FIG. 7.** Houston wholesale power price duration curve. Source: ERCOT.

Another aspect of the ERCOT market that particularly favors storing high volumes of hydrogen is high variance between typical summer and winter energy costs. This results from the competitive market structure in ERCOT, which pushes prices up during high demand periods and correspondingly results in low spot market prices during low demand periods.

As shown in the figure below, the high seasonal price differences provide an opportunity for energy arbitrage. In summer, the variance between high and low-price hours is 6.3 times, and in the fall, it is 3.4 times, suggesting the strong potential for long-duration storage leveraging H2.

[45] ERCOT Electricity Generation Mix, 2019

[46] Hydrogen: A renewable energy perspective, International Renewable Energy Agency, Abu Dhabi. https://www.irena.org/publications/2019/Sep/Hydrogen-A-renewable-energy-perspective




Hydrogen could be produced during typically low-price periods in the winter and stored in the salt caverns along the Texas Gulf Coast. Power could be produced using this stored hydrogen during peak demand periods, including the hottest days of the summer or during extraordinary winter events such as this past February.

Hydrogen for storage would be produced in Texas not only seasonally, but daily during periods of low demand. The competitive market results in daily occurrences of mismatched wind or solar supply vs. demand.

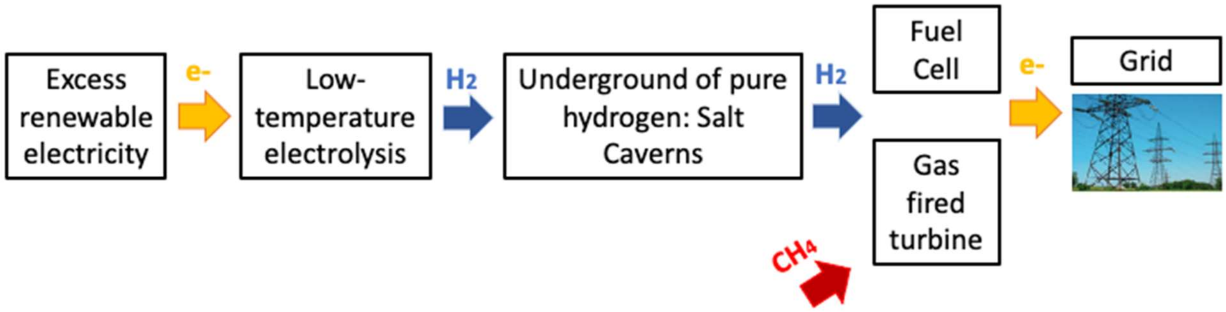
<u>Salt Cavern Storage</u>

As discussed in section 1, the Houston region has three existing utility-scale H2 storage facilities developed in salt caverns.

Coupling H2 salt cavern storage, uniquely prolific in the Texas Gulf Coast area, with low-priced power creates the opportunity to reduce the cost of green hydrogen production, for potential use in seasonal storage (i.e., hydrogen serves as a mechanism to store energy during periods of low cost power in the winter, to be used during peak power prices in the summer) and long-duration H2 storage ( i.e., hydrogen serves as a mechanism to store energy during periods of high renewable power input such as sunny days or weeks, and provides power during periods of shortage such as cloudy days or days with no wind).

### *4.B What are the challenges with storing and production of hydrogen from the project at scale to support grid resiliency?*

The process for producing energy storage from hydrogen would be as follows: The excess energy produced by renewable sources is supplied to the grid. This energy is then used as power input for the low-temperature electrolysis process in which hydrogen is produced. This hydrogen is then carried by pipelines or trucks for storage in underground salt caverns. later, it is converted by fuel cells or gas-fired turbines to electricity again. In turn, it supplies the grid, satisfying an immediate electricity demand requirement.




There are significant technical challenges required to develop long duration energy storage, but none are insurmountable given that this system leverages existing and well-understood technologies used in other applications.

This section will focus primarily on the technical issues of using salt caverns for hydrogen storage under high pressure conditions that include issues such as material compatibility, testing requirements  and microbial activities.

Materials compatibility: Elements that will be in contact with the hydrogen, such as elastomers, packers, valves and slam shut valves (SSV), must be impermeable to hydrogen and resistant to hydrogen embrittlement.[47] The compatibility of the casing, tubing, and wellhead steel with hydrogen must tested to detect damage by hydrogen embrittlement; Suitable corrosion-resistant stainless steel should be chosen for hydrogen storage caverns. Also, joints in piping and tubing would preferably be made by welding or brazing. Flanged, threaded, socket or suitable compression fittings may be used.[48]

Another critical element of the cavern is the cement. It´s essential to ensure the cement's composition remains tight and stable with H2. Natural gas storage wells in salt in the US Gulf Coast have a last cemented casing of 16" or 20", which can conflict with converting natural gas storage to hydrogen storage because the large casing is welded. This, in turn, can be a weakness point for hydrogen integrity. Packers of such large size are not industry standard and most likely have not been tested yet for compatibility with hydrogen.

Testing: Another challenge is the testing to check cavern tightness and integrity. A mechanical integrity test (MIT) is necessary to prove the gas tightness of a salt cavern. This test is carried out by injecting brine and nitrogen into the flooded cavern to reach the operational pressure and by filling the well and the upper part of the cavern neck with the test gas. By metering the encased gas volume or by periodically refilling the test volume, a leakage rate can be derived and

[47] These issues are taken from a presentation by Greenstock Green Storage
[48] Hydrogen Technologies Safety Guide C. Rivkin, R. Burgess, and W. Buttner, National Renewable Energy Laboratory

compared to the test criteria. Many natural gas storage facilities are 30-60 years old; therefore, the conversion to hydrogen storage must first be assessed.

Microbial activity: The last point that should be studied is microbial activity with H2. Only limited research has been performed to understand the geochemical and microbiological reactions and other subsurface processes in these reservoirs. The storage of town gas (H2, CO and CH4) showed, in some cases, an increased micro-bacterial activity can sometimes lead to hydrogen sulfide production.

### *4.C Are there opportunities to utilize hydrogen power to ensure cybersecurity?*

The Center has not examined this issue.

## 5. Greenhouse Gas (GHG) and Pollutant Emissions Reduction Potential (Please quantify the amount of emissions reduction anticipated and in what timeframe.

a. **What is the carbon dioxide emissions reduction potential (in tonnes per year) from cradle to plant gate and in what time frame?**
b. **For complete pathway (production, delivery, storage, end use), specify total GHG reduction potential if available. Also, specify the boundary conditions for the life cycle emissions (upstream, within production plant gate, and downstream for end use).**

The challenge of decarbonizing Houston's industrial sector could be accelerated with the development of a low-carbon hydrogen hub and carbon capture demonstration projects.

The Houston region has been recognized as a prime location for CCS projects given its high concentration of industrial facilities, high level of CO2 emission and density of infrastructure needed in support.

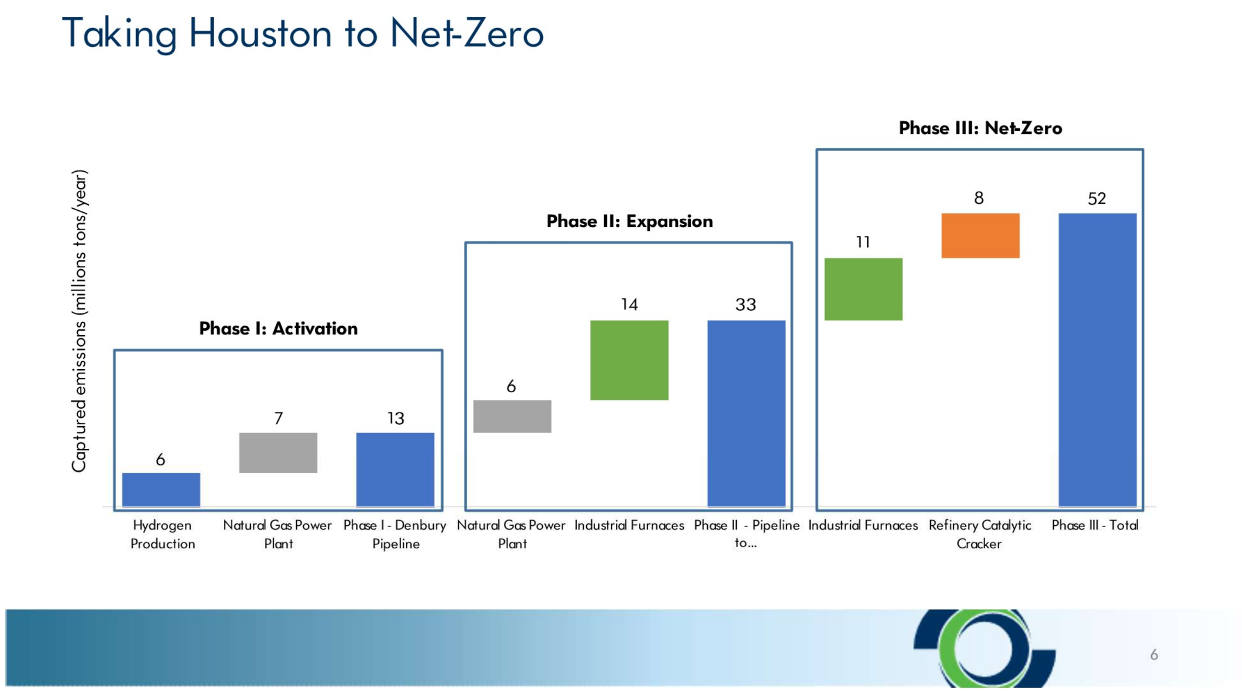
As discussed above, the Center, with University of Houston, studied the potential for decarbonizing Houston's industrial sector.[49] The total potential reduction of CO2 emissions to bring the Greater Houston to net zero is estimated to be 52 million tons per year for Harris, Galveston and Chambers counties.

The study concluded that there are significant near-term opportunities to start with SMR facilities, which have the highest CO2 concentrations and therefore represent the best early targets for carbon capture.

The research demonstrated a potential reduction of between 9 million tons and 14 million tons per year by installing CCS on H2 plants by 2030 (see figure below).

A summary of the report's conclusions is below. While beyond the immediate scope of this RFI, we have included this information so that the Department can evaluate how a hydrogen demonstration project that starts with creating near-term opportunities for carbon capture might fit into an overall framework for reducing industrial emissions in the Houston region. As discussed below, the initial phase of the project, which would involve decarbonization of an existing SMR, would create the learnings and opportunities to expand into the subsequent phases.

[49] Carbon Capture, Utilization and Storage – Lynchpin for the Energy Transition, March 2021 https://www.centerforhoustonsfuture.org/energy




Phase I: Activation (2020-2030)

The work by University of Houston and CHF showed that there is an opportunity to reduce more than 12 million tons of emissions per year by focusing on available strategic assets as SMR (Steam Methane Reforming) plants representing 5.7 million tons/year and 7 million tons/year from natural gas power plants. These facilities require the lowest-cost capture investments and minimal connection investments to pipeline and geologic targets. This first phase would leverage existing CO2 pipeline infrastructure such as the Denbury pipeline which has around 13 million ton/year of available capacity. The third important asset available is the geological storage next to this pipeline, which can receive 1 trillion tons into saline storage formations both on and offshore.

Phase II: Expansion (2030-2040)

During the next phase, the report anticipated capturing the remaining 6.4 million tons/year of CO2 from natural gas-fired power plants and 13.5 million tons/year from refining, petrochemicals, and other industrial processes, including SMRs.

It envisioned expanding a CO2 pipeline network for east and central Texas and into the Dallas-Fort Worth basin to provide as much as 30 million tons/year of capacity to reach additional geologic storage. The Dallas-Fort Worth area is estimated to have 3.6 billion tons of available geologic storage for enhanced oil recovery and 500 billion tons of saline storage. The cost of a 250-mile pipeline expansion is estimated at $500 million.

Phase III: Broad Deployment (2040-2050)

Phase 3 was designed to take the Greater Houston region to net-zero and would move beyond a three-county region to stretch south and east along the Gulf Coast.

In the phase, efforts would expand to include 11.4 million tons/year from industrial furnaces and 7.8 million tons/year from refinery catalytic cracker facilities, fully capturing the region's existing CO2 emissions. It also envisions building a 500-mile CO2 pipeline from Houston to the Permian Basin that would be able to transport 20 million tons/year and would cost between $1 billion and $2 billion. It is estimated the Permian Basin would provide an additional 4.8 billion tons of storage for EOR and 1 trillion tons of storage in saline formations. It would allow industries from across the United States to use these geological assets in Texas.

## Diversity, Equity, Inclusion (DEI), Jobs, and Environmental Justice

6. **Please describe any additional opportunities for DEI, as well as environmental justice andthe potential to positively impact underserved communities.**[9]

### a. Describe community stakeholder engagement opportunities.

The Center recognizes community stakeholder engagement will be the key to success for any hydrogen project and that lack of stakeholder support can undermine the potential for success.

A California case study highlights the importance of engaging with local stakeholders and articulating local benefits.[50] There, Hydrogen Energy California, based in Kern County, CA, sought to use coal and refinery waste to generate hydrogen for electricity while capturing and storing 90% of carbon emissions to use for enhanced oil recovery. Community stakeholders were concerned by the air pollutants emitted, water required and fertilizer byproducts of the project. Ultimately, the project collapsed due to a myriad of unresolved issues.

The Center's work by its nature involves engagement with NGOs, businesses, and state/federal level agencies. In all of our work, we seek to include a wide variety of organizations with an interest in issues where the Center is working.

The Center is the process of identifying those interested parties and is at the beginning stage of creating a transparent, collaborative approach for its clean hydrogen vision. We are in the process of consulting with well-known local environmental organizations such as the Houston Advanced Research Center, a non-profit focused on analyzing the intersection of air quality and environmental justice in developing our workplan. There are other local environmental organizations such as Air Alliance Houston and One Breath Houston that could be interested in our work.

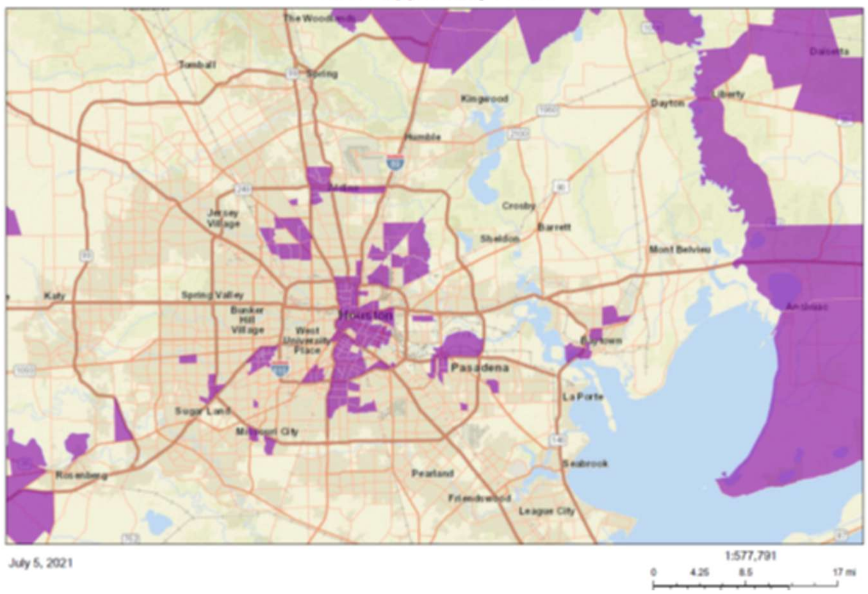
[50] The Kern case is discussed in the California Carbon capture action plan . https://sccs.stanford.edu/events/action-plan-carbon-capture-and-storage-california-opportunities-challenges-and-solutions

b. Describe opportunities to improve historically underserved communities.
c. State whether the region is a considered a distressed community. Would the project(s) be on tribal land?

Below we discuss our initial efforts to better understand the opportunities to improve historically underserved communities and distressed communities and how a clean hydrogen demonstration project can begin to address issues faced by these communities.

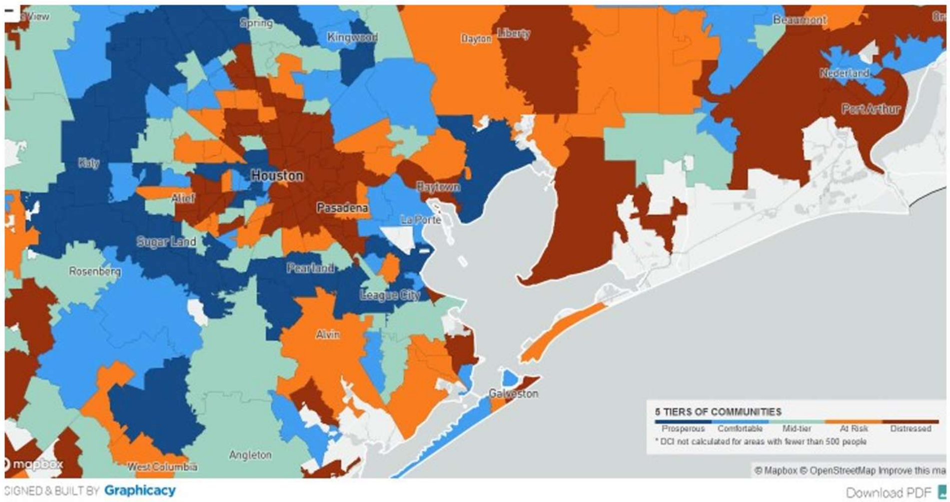
For the purposes of this RFI response, the Center is considering an underserved community as defined by the 99 census tracts in the Houston region meeting the criteria of a Qualified Opportunity Zone as defined by the state of Texas and the City of Houston, and as shown below.

Texas Opportunity Zones




Many of these same communities would also meet the definition of an economically distressed community with high unemployment rates, high mortgage foreclosure rates and declining home prices. The chart below shows those distressed communities identified using the Distressed Communities Index developed by the Economic Innovation Group.[51]

[51] Distressed Communities Index, https://eig.org/dci




In undertaking this work, we are building on research already developed by organizations such as the Houston Advanced Research Center (HARC), which has done extensive work on air quality, emissions, and public health analysis. The HARC work has created overlays using the CDC's Social Vulnerability Index data, which ranks census tracts on 15 social factors, including poverty, lack of vehicle access, and crowded housing, and the Environmental Justice Indexes in EJSCREEN (US EPA), which reflects the 11 environmental indicators, such as National Scale Air Toxics Assessment Air Toxics Cancer Risk, Traffic Proximity and Volume or Proximity to Treatment Storage and Disposal Facilities.

In addition, we are examining web-based tools such as HGBEnviroScreen, which examines environmental justice issues in the Houston region and integrates and visualizes national and local data to address regional concerns across five domains: (i) social vulnerability, (ii) baseline health, (iii) environmental exposures and risks, (iv) environmental sources, and (v) flooding. [52]

This will allow us to identify the highest vulnerability census tracts that have multifactorial risk factors, with common drivers being flooding, social vulnerability and proximity to environmental sources.

Leveraging our work with HARC, we plan to examine the interface between air quality, emissions, and public health analysis through the following types of analysis:

- Developing sectoral emissions inventories (for criteria pollutants, air toxins, and greenhouse gas emissions) utilizing various emission models and methodologies including EPA's MOVES and SMOKE models to analyze emissions for various scenarios.
- Establishing air quality modelling forecasting frameworks for the Houston region using CMAQ and CAMx for hourly concentrations of gas-phase (e.g., ozone, NO2, CO, air toxins,

[52] HGBEnviroScreen https://hgbenviroscreen.org/home. See also, Bhandari,et. al., HGBEnviroScreen: Enabling Community Action through Data Integration in the Houston–Galveston–Brazoria Region, https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7068489/

etc.) and particle-phase (e.g., PM2.5, etc.) species to assess the ambient air quality implications of various scenarios/policies.

- Undertaking a health impact assessment utilizing the U.S. EPA's BenMAP-CE model to estimate the possible health benefits or damages due to changes in air pollution concentrations related to the various H2 production and penetration scenarios. This will include potential associations of morbidity and mortality and the health and cost impact caused by changing ambient air pollution concentrations influenced by various H2 policies.

Our research has shown that hydrogen transportation projects can begin to address systemic environmental issues.

A recent paper by scientists at Texas A&M shows that moving to 40% medium- and heavy-duty trucks which are zero emissions either through hydrogen or electrification would reduce 21 tons/day, or about 25%, of on-road mobile source NOx emissions in the H-GAC 8-county area in 2020. The report shows that heavy-duty long-haul trucks present the highest reduction potential and that these reductions will more likely benefit more low-income communities. [53]

7. **Please specify the job opportunities in the region that would be available because of theproposed project(s).**

**a. Indicate gross versus net jobs.**
**b. Indicate the sustainability of the jobs.**
**c. Indicate the number of jobs required for installation versus subsequent maintenance, manufacturing, or other ongoing service jobs in the region.**
**d. Indicate any opportunity zones in the region, including tribal lands, Historically Black Colleges and Universities (HBCUs), or other minority serving institutions.**

According to the recently released study by McKinsey and Company on Houston's energy transition for the Greater Houston Partnership, an estimated 24 percent of Houston's jobs are in upstream, midstream, refining and petrochemicals. When considering indirect and induced jobs related to the energy sector, this figure reaches roughly 40 percent of the region's total jobs.[54]

The study found that Houston could lose 270,000 jobs over the next 30 years under a Business-as-Usual Scenario if current trends in energy demand and gains in production efficiencies continue. That number could rise to 370,000 jobs if the world follows – as seems likely – an Accelerated Transition Scenario to low-carbon energy or up to 650,000 jobs in a 1.5C Pathway that calls for CO2 emissions to drop by 90 percent by 2050.

[53] Meitiv and Xu, Tailpipe Emission Benefits of Medium- and Heavy-Duty Truck Electrification in Houston (2021) https://www.utilitydive.com/news/cleaner-by-the-mile-electric-trucks-can-have-outsized-environmental-and-he/598369/

[54] Houston: Leading the Transition to a Low-Carbon World, https://www.houston.org/energyconference

On the other hand, the study found that a low carbon hydrogen strategy could be a growth driver and create 53,000 new jobs by 2030 and potentially up to 113,000 new jobs by 2050.

Growth in the hydrogen and fuel cell industries will lead to vast new employment opportunities, and these will be created in a wide variety of industries, skills, tasks, and earnings. Many of these new jobs are expected to generate sustainable, high paying jobs.

One study identified 42 emerging occupations with a projection for expansion as the fuel cell and hydrogen industries mature.[55] Along with these newfound opportunities, science and engineering education, student career connections, and training will be bolstered to support this new supply of jobs. Jobs available range from fuel cell engineering to quality control and has a wide range of skills and degrees required that can assemble a workforce with diverse backgrounds and salaries. Apprenticeships and internships are also available, thus ensuring both a training pipeline and accessibility. 3% 30%
12%15% 15% 15% 32% 19%
12%8%8% 40%

8. **In regard to environmental justice communities/neighborhoods that could make better useof minority serving institutions, or could benefit DEI/underrepresented groups (URG) through internships or training opportunities, please identify:**

In June 2021, The Texas State Legislature passed a bill establishing the Texas Reskilling and Upskilling through Education Program to support workforce education.[56] The Texas Higher Education Coordinating Board, together with public junior colleges, will develop new industry certifications according to the skills required by high-demand industries. The clean and renewable energy sector is rapidly growing and is a good candidate for these skillsets.

Two of Texas's nine historically black colleges and universities, Prairie View A&M University and Texas Southern University, are within Greater Houston. The implementation of workforce training programs at these universities is an opportunity to provide jobs to underrepresented groups in a growing job sector.

9. **Please provide input on any fundamental science, basic or applied research, and innovation needs and challenges that may be required for, or be informed by, thedemonstration projects. In addition, please identify scientific user facilities or computational tools that would provide the required innovations or resolve the remainingchallenges.**

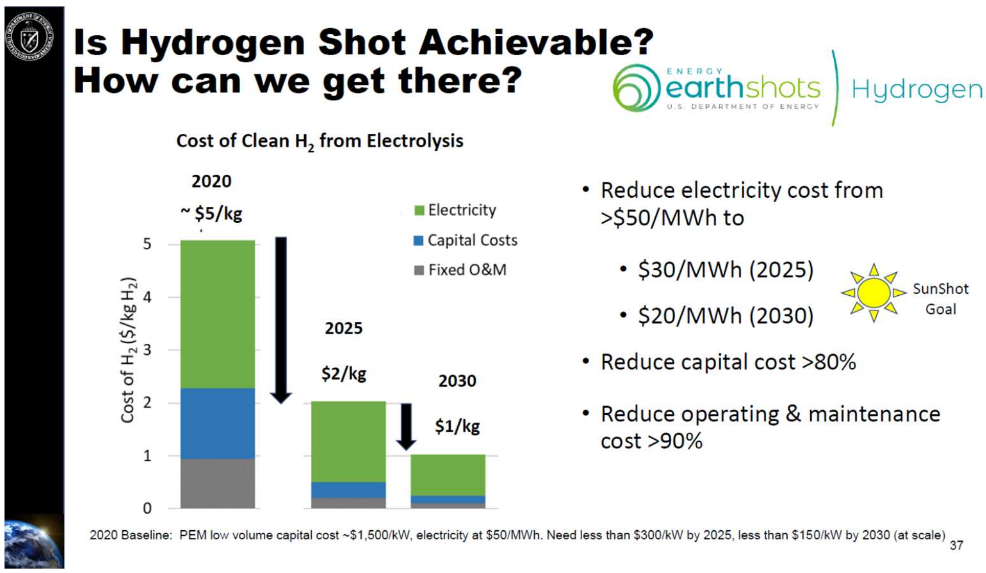
10. **Are there systems integration or prototyping facilities available or needed that couldbenefit the project and de-risk large-scale deployment? Please describe any testing facilities that could be used or are required.**

[55] Bezdek The hydrogen economy and jobs of the future (2019) https://doi.org/10.1051/rees/2018005

[56] Texas Senate Bill 1102 https://legiscan.com/TX/bill/SB1102/2021

Questions 9 and 10 are addressed below. This section will focus primarily on describing challenges related to DOE's goal of reducing the cost of electrolysis by 80% over the next decade and of developing the technology to deliver hydrogen to end users. We assess the role of Houston and Texas-based organizations in addressing these challenges.

As identified at the recent hydrogen DOE Annual Merit Review, the Hydrogen office presented data showing that reaching the Earthshot goal of $1/kg will require cost reductions across the board: in electricity costs, capital costs and operations and maintenance.




There are several ways in which creating a Houston-based clean hydrogen hub would help DOE in meeting these goals.

First, major Texas universities have extensive energy research capacity that can be applied to fundamental hydrogen R&D. These include:

- **Rice University's Carbon Hub** is focused on fundamental research for creating new applications for clean hydrogen energy and advanced carbon materials co-produced efficiently and sustainably from natural gas and oil.
- The **University of Houston's Center for Carbon Management in Energy** is focused on research and development related to low-carbon energy.
- The **University of Texas' Center for Electromechanics** is currently participating in an H2@Scale project and the **UT Energy Institute** integrates technological knowledge with the reality of politics, regulation and the marketplace.
- The **Texas A&M Energy Institute** has an extensive research program that connects engineering, sciences, technologies, economics, law and policy decisions.
- **Houston Advanced Research Center (HARC)** is undertaking a number of activities to assess the technical and economic opportunity of deploying microgrids or district energy

systems. This allows end-users to assess feasibility of a variety of distributed energy generation applications, including hydrogen-fueled combined heat, power, and fuel cells.

Second, Houston has recently taken many steps to begin moving innovations out of the lab and into the marketplace. The recent openings of Greentown Labs, the nation's largest clean energy accelerator, and The Ion, a co-working space focused on creating an innovation ecosystem, are examples of a developing ecosystem, which can focus on commercializing and reducing the cost of clean hydrogen technology.

Third, the challenge of scale and cost reduction highlights the significant role that Houston could play in a clean hydrogen demonstration project. A recent report by Boston University's Institute for Sustainable Energy identifies scale as the most significant part of the hydrogen challenge. [57]

As the BU report makes clear, how much of this investment occurs in the United States will depend on bridging gaps in support for technology scale-up and integration. Many countries are already investing large sums in commercial-scale demonstration projects that intended to attract even greater private sector investment. For example, the EU and many of its member states are making major investments in the electrolyzer supply chain and prototype and demonstration production plants.

The BU report makes recommendations that all argue in favor of a Houston-based hydrogen hub. Those include:

- R&D: Build "strong linkages" across DOE's hydrogen innovation pipeline from basic research to commercially oriented demonstration projects.
- Demonstration: Create hydrogen hubs that "encompass both blue and green hydrogen production in a range of configurations as well as diverse end uses, informed by a strategic analysis of the competitive advantage of U.S. locations."
- Deployment and market expansion: Focus on the "bankability" of clean hydrogen production.
- Innovation ecosystem: Improve the current understanding of job and value creation in a rapidly changing industry.

As we have discussed, Houston has many strengths in these areas.

Lastly, implementation challenges such as hydrogen safety issues, the overhaul of the power grid, development of transportation infrastructure, and compression technologies are all necessary to implement clean hydrogen energy on a large scale and are all areas in which Houston-based companies can significantly contribute.

[57] 2021 Clean and Competitive: Opportunities for U.S. Manufacturing Leadership in the Global Low-Carbon Economy. Peter Fox-Penner, David M. Hart, Henry Kelly, Ryan c. Murphy, Kurt Roth, Andre Sharon, and Colin Cunliff. June 2021. http://www.bu.edu/ise/research/clean-and-competitive-opportunities-for-us-manufacturing-leadership-in-the-global-low-carbon-economy/

In sum, the creation of a Houston-based hydrogen demonstration project would be an important step in addressing DOE's goals for accelerating development of hydrogen as a decarbonization strategy.

**Conclusion**

The Center for Houston's Future believes Houston should be a site for a DOE hydrogen demonstration project that will help achieve DOE's vision for tackling the toughest problems to deploy clean energy technologies at scale.

From President Kennedy's historic Moonshot speech at Rice University to U.S. Energy Secretary Granholm's announcement sixty years later of the Energy Earthshot and its ambitious Hydrogen Shot goal of 1 by 1 by 1, it is clear that Houston, as the Energy Capital of the World, is ready, as Rice University historian Douglas Brinkley has said, to "once again do bold things" by addressing climate change.

Respectfully Submitted,

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