CENTER FOR HOUSTON'S FUTURE

Houston Region: Becoming a Global Hydrogen Hub

Hydrogen industry growth can drive diversification needed to sustain Houston's economic advantage.

In 2019, the Center for Houston's Future (CHF) released an economic viability study that assessed Houston's long-term economic outlook given the close ties between the oil and gas (O&G) sector and the region's economic success.

The study found that Houston had outperformed economically versus peer cities, and that this growth was driven primarily by the O&G sector. Looking at the impact of the 2014 oil price crash, the study found that 80,000 O&G related jobs lost in the fallout of the 2014 oil price decline were:

- high-multiplier jobs, or jobs that spur additional economic activity in the region, resulting in higher economic impact than other jobs.
- not replaced with commensurate jobs once the region's job growth rebounded. (see Figures 1 and 2 below).

As a result, the study found that Houston's growth story had shifted: Houston's economy has since been growing slowing than peer cities as new jobs added after the oil price rebound had lower multipliers, whereby resulting in slower GDP growth. Examples included temporary roles and construction jobs driven by Hurricane Harvey recovery, and hotel, restaurant and retail industry expansion resulting from the earlier high economic-growth period. As shown in Figures 1 and 2, the jobs lost during this time period had a 2.9x multiplier (meaning that they created 2.9x additional jobs) and the jobs gained had only a 1.66x multiplier.

Figure 1. Jobs lost and multiplier

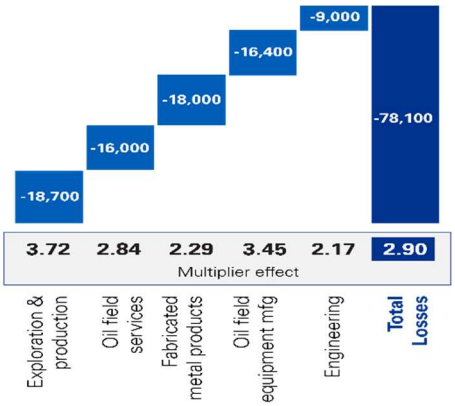
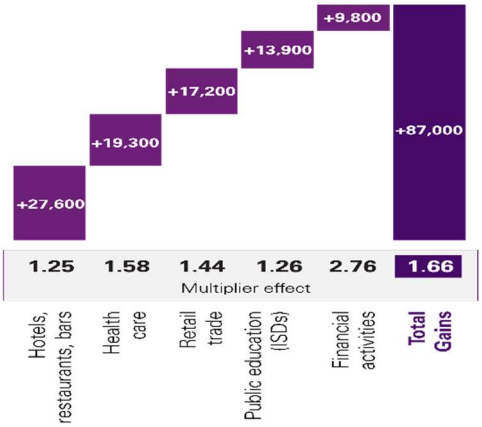


Figure 2. Jobs gained and multiplier



As a result, in the 2019 report, we concluded the Houston region should not rely on an oil and gas industry rebound alone to create or recreate high-multiplier jobs. That was the case, even as we found that oil and gas was expected to remain a large and critical part of our economy.

We also concluded that the Houston area required economic diversification to sustain a growth rate greater than peer cities. Even then, we saw competition from new energy sources and that the oil and gas industry was becoming more efficient, requiring fewer workers to achieve similar output.

The study also identified high multiplier-job sectors where the Houston Gulf Coast region has the 'rights to win'.

Developing a broader hydrogen (H2) economy, for example, was identified as an option among other low-carbon leadership opportunities that would result in new high-multiplier jobs in a sector that would let us use the region's significant skills and capabilities.

Houston's business and civic leaders now face the apparently more imminent effects of an increasing global shift toward decarbonization.

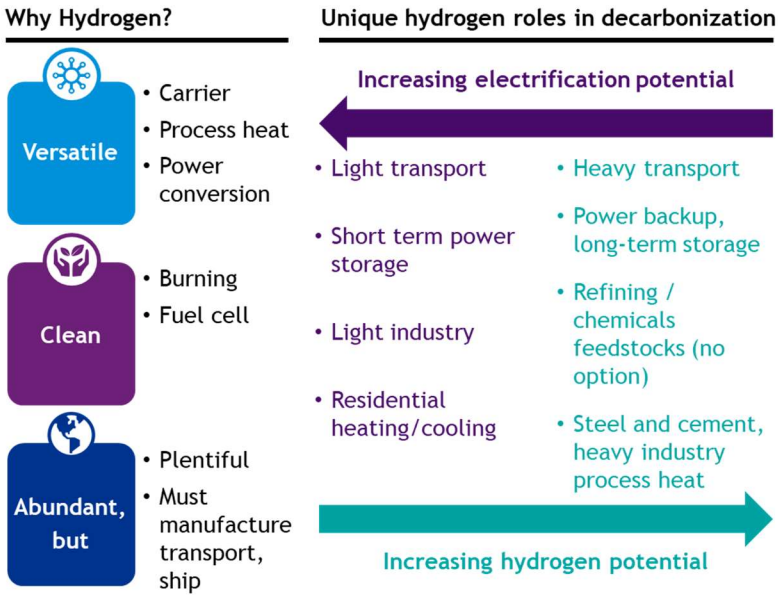
Amid these headwinds, we saw further interest in exploring the viability of growing the clean H2 economy in Houston.

CHF, University of Houston and other key collaborators stepped in to identify opportunities for expanding clean H2 value chains in the Houston region and to develop a vision and roadmap to enter and expand markets for hydrogen. We looked beyond existing hydrogen use in the Gulf Coast, which is predominantly refining and petrochemicals.

There is snowballing momentum to decarbonize, with hydrogen potentially playing a unique and critical role

Global decarbonization momentum has increased the focus on the unique and many roles of hydrogen in a low-carbon energy system.

Figure 3: Hydrogen's unique advantages and decarbonization role



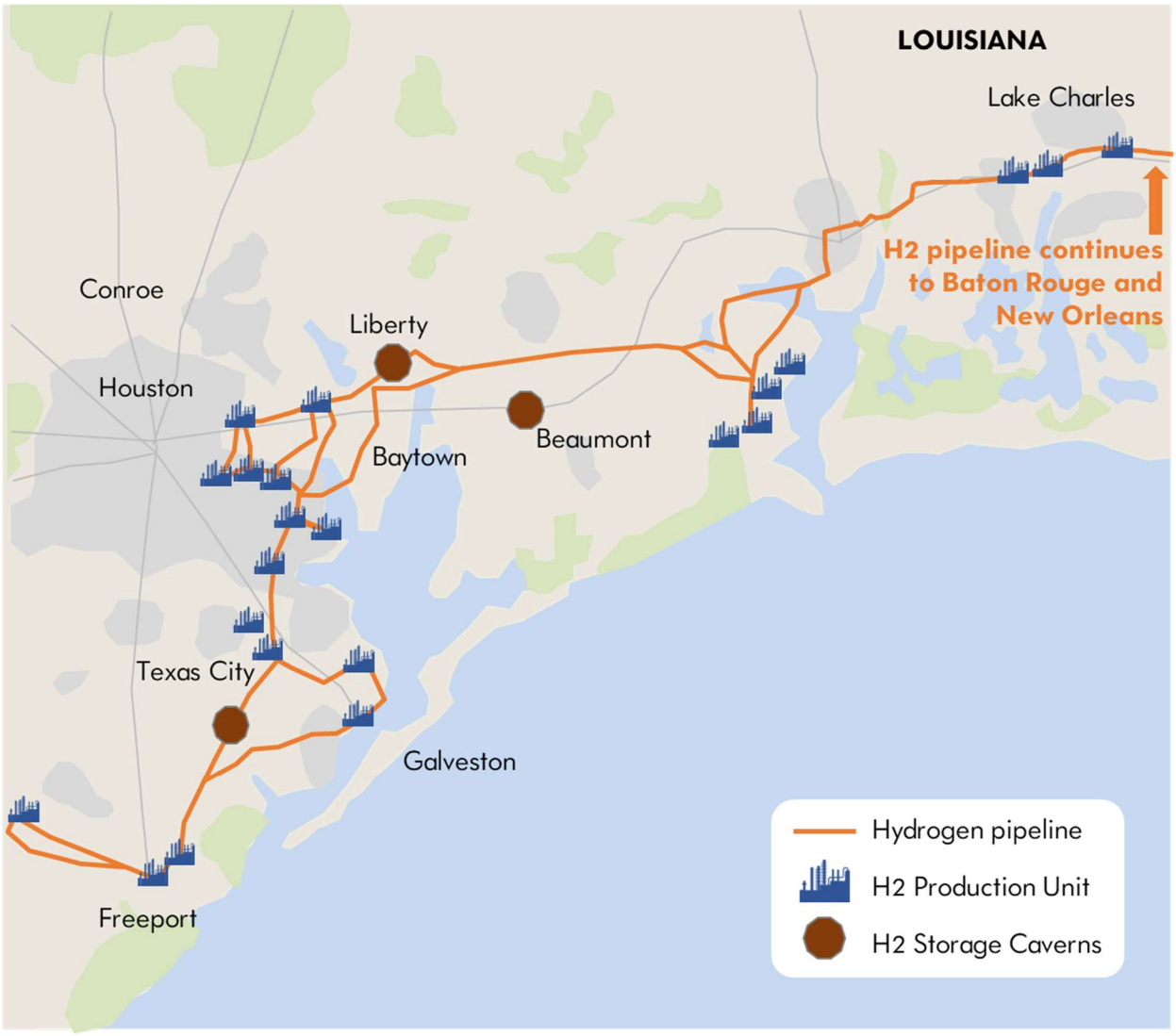
Since the start of 2020, multiple regions have developed strategies to use hydrogen in achieving decarbonization goals, including the European Commission and several European countries (Germany, the Netherlands, Norway, Portugal, Spain, France).

Preeminent energy companies, including Shell, BP and Repsol, have also made low-carbon commitments and announced plans for H2 projects to help them meet their commitments. Such plans help explain why substantial growth in the market for hydrogen gas is projected, increasing by approximately $800 billion by 2050.

Houston could play a unique role in the hydrogen economy

The Houston Gulf Coast area anchors the world's leading hydrogen system, producing approximately 1/3 of the US's total H2 gas annually, and encompassing an expansive system of 48 H2 production plants, over 900 miles of H2 pipelines (more than half of the US's H2 pipelines and one-third of H2 pipelines globally), as well as geologically unique and at scale salt cavern storage, as shown in Figure 4.

Figure 4: Existing hydrogen system in the Houston region



Source: H2Tools, USDOT – PHMSA, Air Liquide, Air Products, Praxair

Today, this system primarily serves the Gulf Coast's refining and petrochemical industry. By leveraging this system, the Houston Gulf Coast area has the potential to bring substantial volumes of H2 to new markets rapidly and at scale.

Priorities for activating H2 expansion and capturing upside are removing CO2 and creating new market infrastructure

There are multiple potential end markets emerging that could be developed in the Houston regions and into which the existing hydrogen system could be extended to support.

Heavy duty trucking has been referred to, for example, as a 'killer app'. The advantages of hydrogen fuel cell power in this application are many: low weight, fast refueling, high range, relatively low new infrastructure costs and emissions reductions. Emissions would be lower even if the hydrogen fuel is 'grey' hydrogen.

Grey hydrogen is the common term for hydrogen produced by the dominant method now used on the Gulf Coast. That is through steam methane reformation (SMR) technology. Natural gas provides the methane input for SMRs. Hydrogen is stripped in the process, creating CO2 as a by-product. Hydrogen produced in this manner is known as "grey" hydrogen.

We concluded that heavy trucking should be an initial priority in the Houston area. We prioritized markets based on: The extent of new infrastructure needed, the competitiveness of hydrogen over existing fuels, and the relative emissions reduction (Figure 5).

Trucking requires limited new infrastructure to enter and hydrogen fuel competes with relatively expensive and relatively higher emitting-diesel fuel.

Moreover, as grey hydrogen is paired with carbon capture and sequestration (CCUS) – creating so-called "blue" hydrogen – the emissions benefit of using hydrogen fuel increases. (CCUS pulls carbon emissions out of the process.)

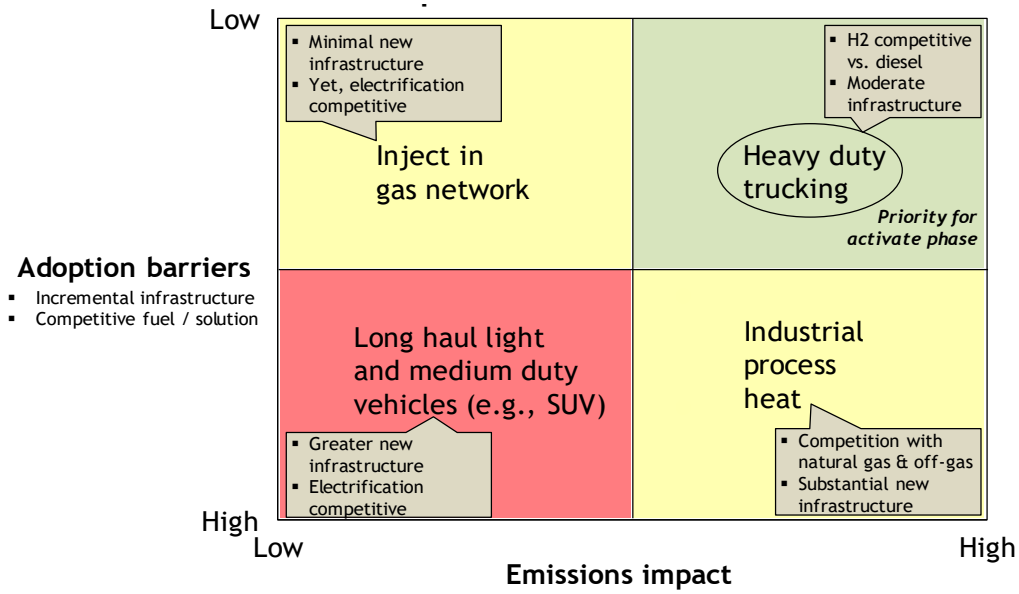
There are multiple market applications for hydrogen beyond its existing use in refining oil and as a petrochemical feedstock. The extensive Gulf Coast SMR system exists today for refining and petrochemical uses, although could be used for other applications.

Industrial process heat, electric power production, and building heating are other potential hydrogen markets in addition to heavy transportation – all of which could be done in the Houston region. And like accessing the heavy transportation

market, each of these markets can be prioritized based on infrastructure investment requirements, comparative economics of hydrogen vs. the existing fuel or energy solution, and the relative emissions reduction impact of using hydrogen vs. the existing fuel.

As hydrogen systems costs continue to improve – potentially accelerated through policy incentives and support – the potential for additional market opportunities only grows.

Figure 5: Initial prioritization of blue H2 markets



Specific to the Houston Gulf Coast area, heavy trucking is particularly attractive as an initial new market.

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

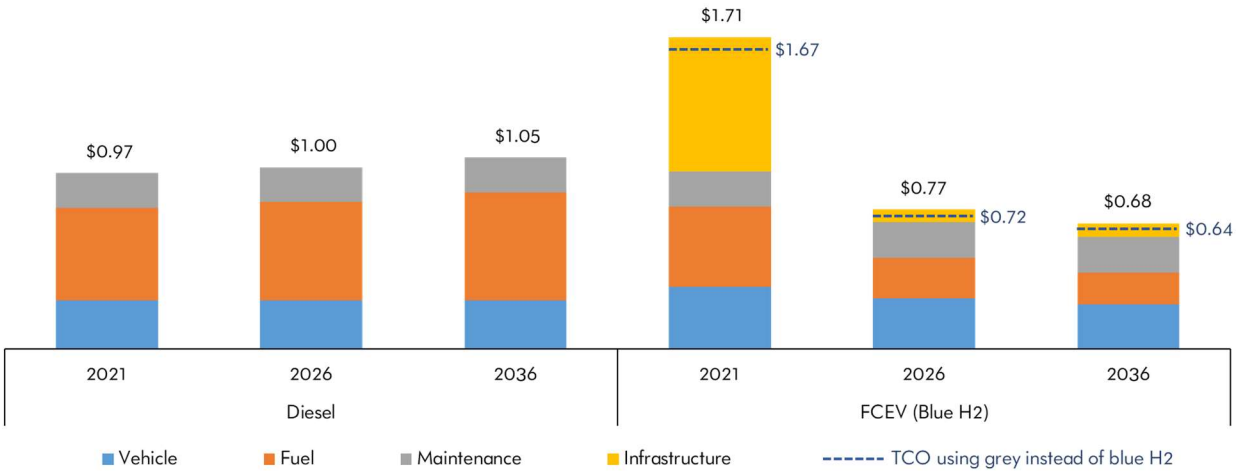
Figure 6 illustrates the potential economics of the I-45 corridor, where a DOE-funded, planning low-emissions study is underway by the North Texas Council of Governments. As with analogous markets such as the Port of LA, economics are favorable for the I-45 corridor at scale.

Coupling this potential with the facts that vehicle manufacturers such as Nikola, Toyota and Hyundai are developing and piloting the manufacture of H2 trucks,

and shippers are increasingly seeking to curb their 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 geographies has been catalyzed by incentives to update truck fleets to lower-emission fuels and to build infrastructure. Incentive requirements would be less here, given the Houston region's current hydrogen production and dense heavy-trucking patterns.

Figure 6: Total cost of ownership for diesel vs. H2 heavy duty trucks on I-45 Houston-Dallas corridor ($M/truck)



Source: ANL: HDSRAM, ICCT, EIA

More specifically, demonstration pilots focused on producing H2 to power fuel cells can be done in the next year or two leveraging the existing low-cost, high-scale Gulf Coast H2 system.

And as stated above, further emissions reductions and value could be achieved if blue hydrogen is the fuel source, which could be the case if we applied carbon capture, utilization, and storage (CCUS) to SMR production.

Applying CCUS to manufacture blue hydrogen as a fuel could be incentivized both by CCUS policy (e.g., the federal 45Q tax credit, possibly with enhancements) as well as a potential clean fuels incentive. California, for example, has adopted a Low-Carbon Fuel Standard. Blue H2 has both Houston-region applications and potential opportunities elsewhere.

For example, a promising early blue H2 opportunity could be exporting to California, to take advantage of its Low-Carbon Fuel Standard incentive. A blue

system, anchored in the Houston Gulf Coast area, could expand to become a major H2 exporter, leveraging its low cost and existing scale position.

Many markets, domestically and globally, will need more H2 than they can produce over the next decade to meet decarbonization goals.

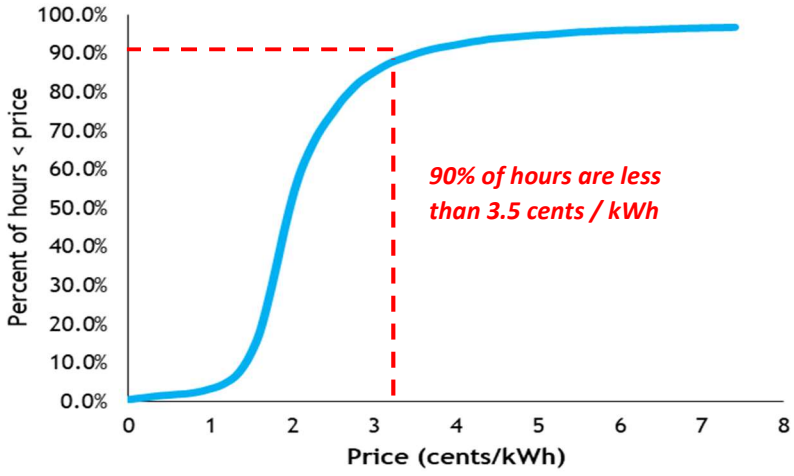
Another H2 priority is initiating green hydrogen value chains to exploit other Houston and Texas advantages

As outlined above, there are clear opportunities to bring grey/blue H2 to market at-scale quickly in Houston and Texas and potentially to export to other regions. Doing so would accelerate decarbonization.

The region and the state also hold significant advantages to incubate green H2, which is produced via splitting a water molecule through electrolysis to create no-emission H2.

One important advantage, given the significant power consumption requirements for electrolysis, is that the Texas power market includes many hours of low-priced power due to a generation mix heavy in wind power (Texas is the #1 wind power producing state), as well as a rapidly growing solar fleet.

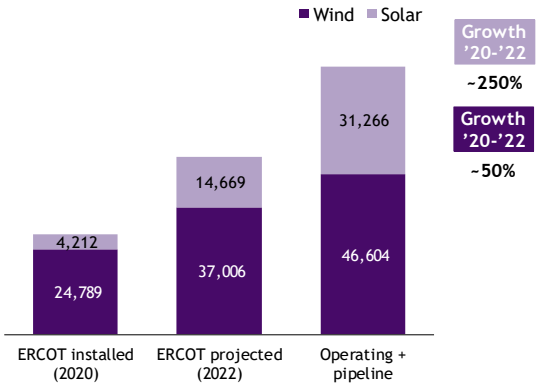
Figure 7 illustrates the effects of this extensive renewable power base on



Source: ERCOT

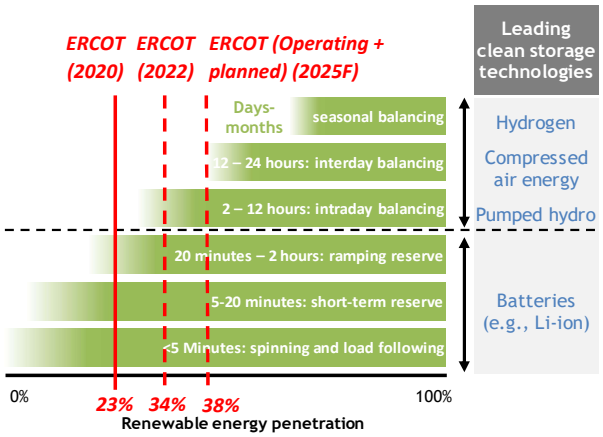
Coupling H2 salt cavern storage, uniquely prolific in Houston Gulf Coast area, with low-priced power creates the opportunity to reduce the cost of green hydrogen production, for potential use in seasonal storage (i.e., hydrogen serves as a mechanism to store energy during periods of low cost power in 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), and other applications outlined below.

Figure 8. ERCOT and Texas installed and potential wind and solar capacity, MW



Source: ERCOT

Figure 9. Energy storage requirements vs. renewable energy penetration levels



Source: ERCOT

Activating both blue and green H2 opportunities centers around four immediate initiatives

We recommend four key initiatives to activate blue and green H2 in the Houston Gulf Coast:

- Launch a heavy trucking pilot.
- Expand the connection of the existing SMR system to CCUS to create blue H2.
- Pilot seasonal storage leveraging Gulf Coast H2 caverns and low-price power.
- Advance additional long-duration hydrogen storage opportunities across the Texas grid.

These activation initiatives will require approximately $565 million over 10 years, appropriate policy changes, and public funding to help defray costs of new infrastructure build-out, equipment change out, and facilitating permitting. Other incentives and policy changes will be needed over time to further develop new chains and markets for hydrogen.

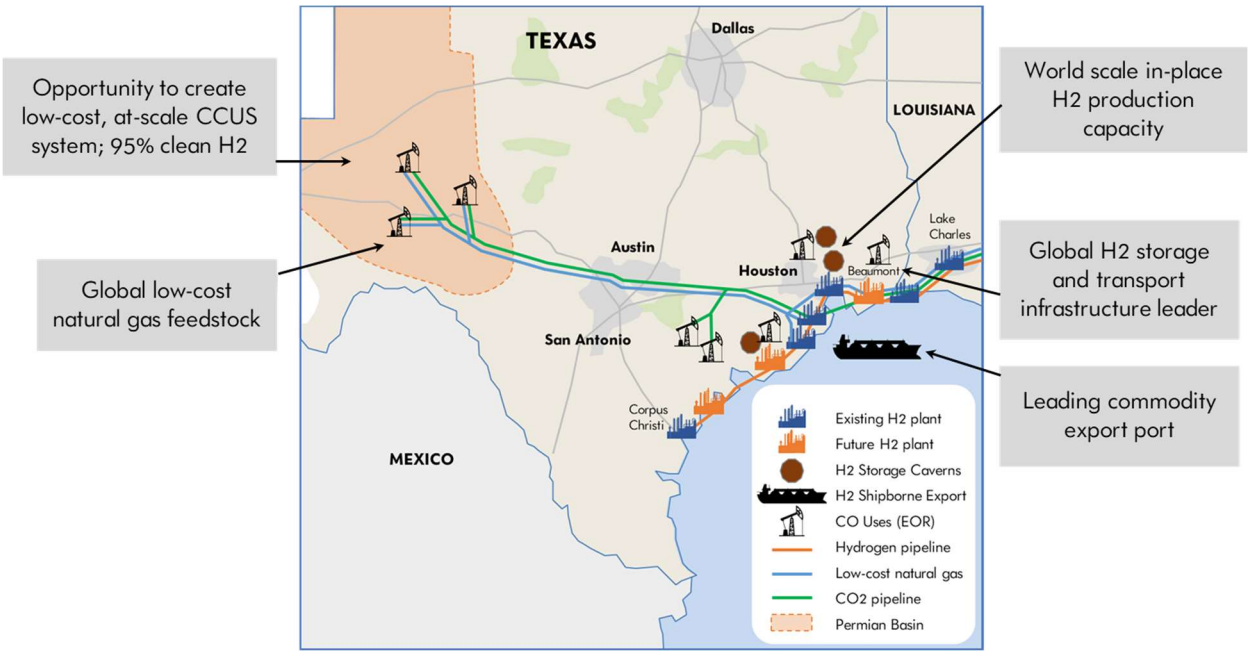
Beyond the 'Activation phase,' there are opportunities in an 'Expand phase' to expand blue and green hydrogen

There are potential opportunities to expand blue and green H2 production in the Houston region, as clean H2 demand continues a sharp increase through 2050.

Some markets, domestic and international, will have to import hydrogen to meet demand. There is a strong case for Houston to become a global blue H2 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.

This could be a mid-term strategy to accelerate at-scale volumes of clean hydrogen to market. That will also address hard-to- abate emissions sectors of the economy.

Figure 10: Case for Houston as global blue H2 exporter



Initial export markets may include domestic markets such as California to exploit the upside with its Low-Carbon Fuel Standard or international markets such as the Netherlands or Germany, which have regional supply projections short of demand requirements.

Capturing full value from new hydrogen market opportunities (assuming incentives for clean hydrogen) will likely require leveraging the existing SMR system and creating new methane based H2 production paired with CCUS.

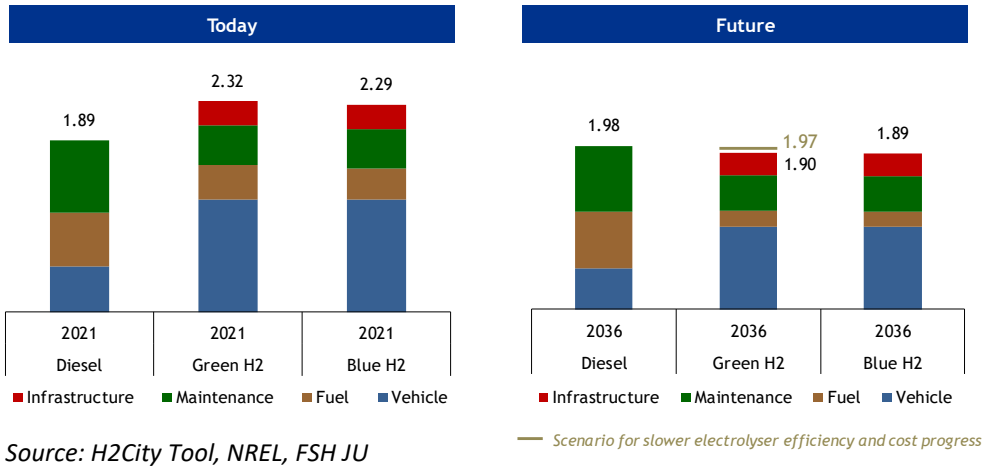
Further, new blue H2 production with even lower net emissions could be realized through constructing plants with alternative technologies, such as ATR (autothermal reforming), as is planned in the Netherlands' Port of Rotterdam and UK Humber areas, and/or incorporating bio-mass feedstocks. Building out the CCUS system required would likely occur in phases:

- First, activate CCUS by filling the Denbury pipeline system with CO2 captured from 8 large SMR plants in the Houston MSA, proximate to the Denbury.
- Second, expand CCUS capacity as needed by building additional CO2 pipeline capacity to exploit CO2 usage and storage opportunities in (1) TX Gulf Cost and (2) extending into the Permian.

There could also be an expanded role for green H2 as renewable power penetration increases, electrolysis costs and production efficiencies improve, and policy/market trends evolve.

For example, green H2 could play a role in decarbonizing bus transportation as an early market opportunity.

Figure 11: TCO for diesel vs. H2 (blue and green) extended duty transit buses ($M/bus)



Source: H2City Tool, NREL, FSH JU

Longer term, how a 'Rollout phase' plays out for H2 in the Houston area is uncertain and depends on a variety of forces

The outlook for a 'rollout phase' given what we know today is uncertain and depends on multiple forces that will significantly shape the demand, pace, and source of H2 in decarbonization.

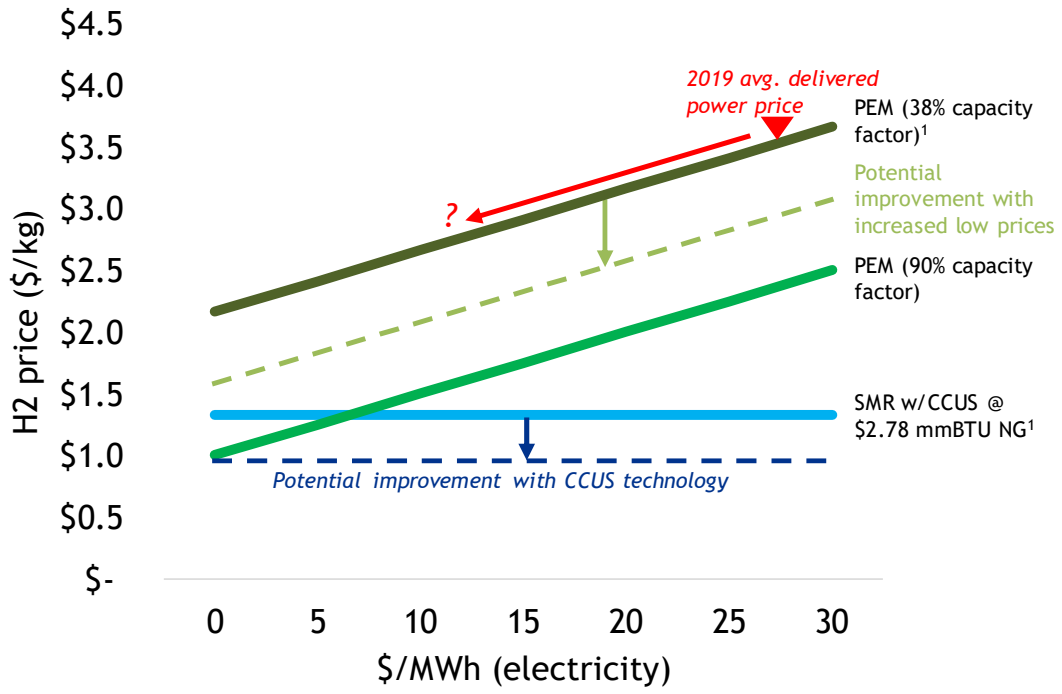
For example, public policy changes, investor preferences, renewable and electrolysis technology, and cost trends, etc. could accelerate green H2 to playing a larger role, sooner.

On the other hand, decarbonization goals and timing, CCUS technology and uptake trends, and public carbon policy could extend the role of blue H2 in meeting rising global decarbonization needs.

Currently, estimated H2 costs to couple SMR production with CCUS is significantly cheaper than green H2 in the Houston region due to existing SMR H2 infrastructure, low natural gas feedstock costs, and the opportunity to leverage and extend existing CCUS infrastructure.

Grey and blue hydrogen is also widely available now, while green H2 is not. However, electrolysis investment costs and efficiency are projected to improve significantly as manufacturing increases and technology advances. That along with the previously mentioned renewable power availability and price reductions and other forces could spur additional green H2 at lower costs.

Figure 12: Current blue and green Houston production costs



***Costs exclude transportation, storage, and dispensing station*

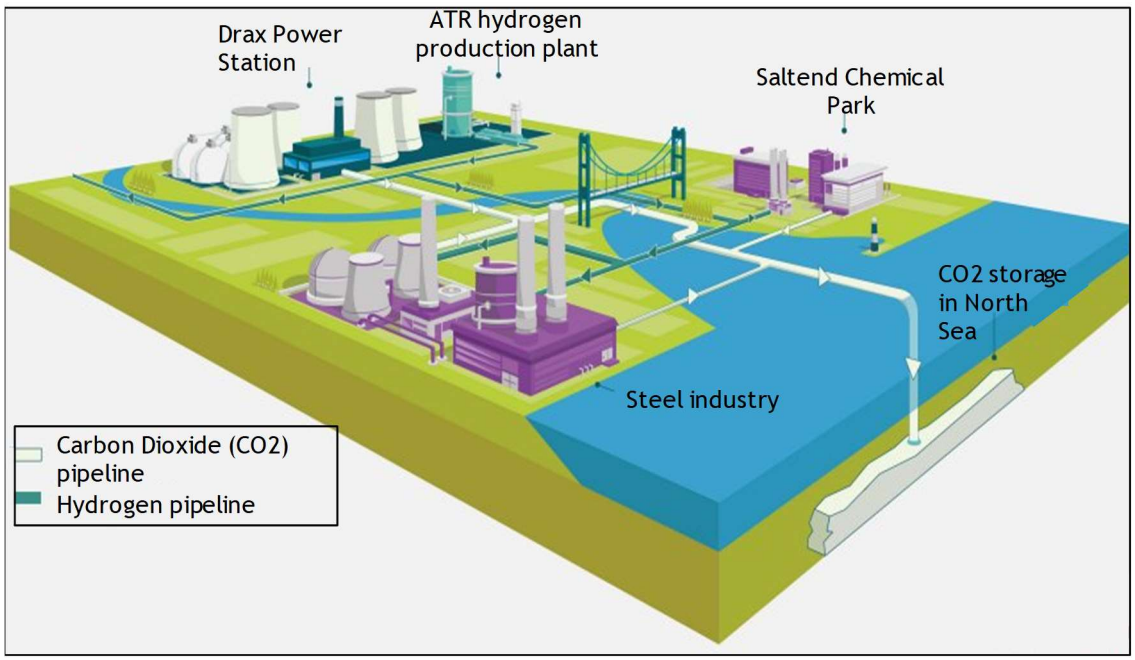
Source: S&P Platts

A key longer-term decarbonization opportunity is reducing emissions in Houston's vast industrial sector

A key decarbonization opportunity is the Houston region's vast industrial sector, which comprises approximately 30% of US refining capacity and more than 40% of US petrochemical capacity.

The region's industrial sector accounts for 40% of TX's industrial emissions, totaling 65 million metric tons annually. Other regions, such as Rotterdam and Humber, UK, have developed plans to use H2 to decarbonize industrial process heat and power by burning H2 instead of fossil fuels.

Figure 13: Schematic of Humber, UK industrial area



Source: Equinor

Adapting infrastructure to burn H2 requires substantial investment, and the Netherlands and UK have instituted carbon taxes along with funding to support investment.

A lack of such a carbon policy in Texas and the US, along with high investment costs, suggest decarbonizing the industrial sector on market-driven forces alone will occur longer term due to improving economics across the hydrogen chain.

Overall, the Houston region has the opportunity to emerge as a leading global H2 hub.

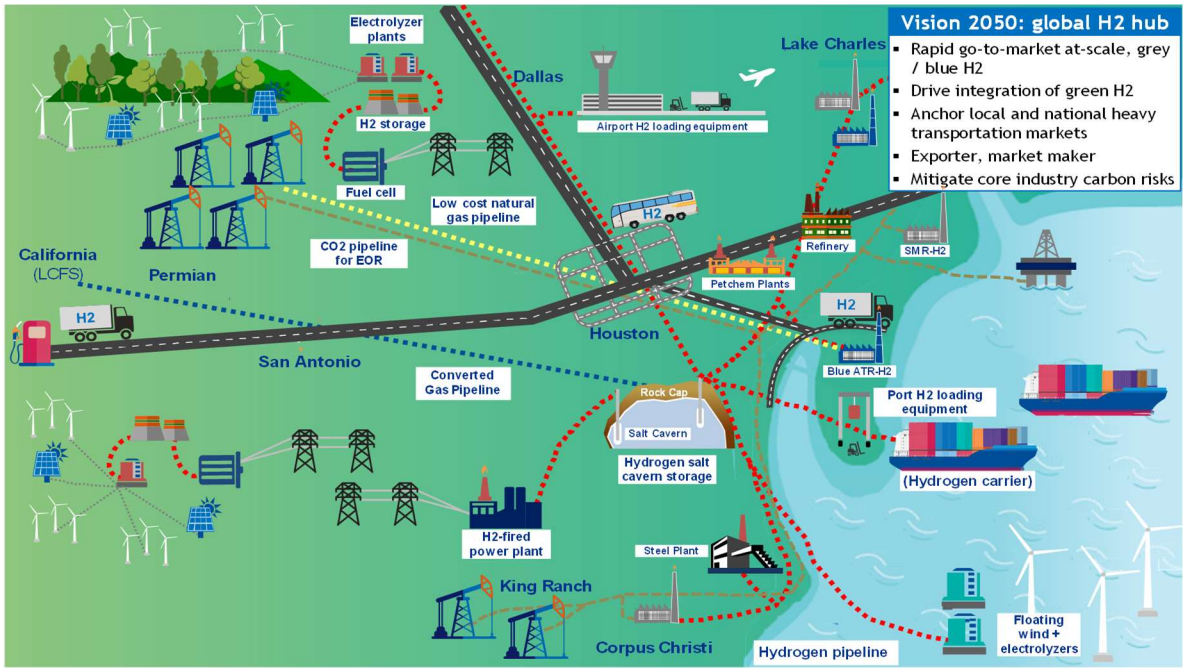
A converging view across the various regions (e.g., most European countries) with H2 plans suggests a larger role for blue through the medium term – now through the 2030's, while at the same time fostering green. The timing and extent of low-carbon policy could change overall H2 demand and as the mix of blue vs. green H2,

Cost-competitive green H2, and the ability to scale, is anticipated in in the 2030's and beyond, as electrolysis costs and technology improve, fuel-cost manufacturing and scale economies improve, and more ubiquitous and low-cost renewable power is available.

The substantial demand for blue hydrogen in the near- and medium term, followed by improving and expanding green H2 opportunities presents a unique opportunity for the Houston region.

Leveraging its world class H2 infrastructure, people and corporate assets, Houston can globalize its hydrogen leadership and emerge as the leading global H2 hub, driving lower emissions globally and bridging between old and new energy systems as a path to sustain economic outperformance.

Figure 14: 2050 vision for Houston region H2 economy



To tap this longer-term potential – as blue and green H2 technologies and costs advance and macro policy goals regarding decarbonization take shape – additional and adaptive policies and funding mechanisms will be required. Early establishment of these policies would help the Houston region keep pace with decarbonization initiatives in other parts of the world.

Summary and Conclusions

Research commissioned for the Center shows that Houston has a significant opportunity to both reduce its carbon emissions from existing hydrogen production while creating new market opportunities from the energy transition. There is no question that the world of energy is changing to impact Houston's

economy, the issue is whether Houston will transition rapidly enough capture these new opportunities. This report shows the pathway forward.

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For more Information

For more information on our work on the energy transition, please check out a full set of materials supporting this perspective.

Additional information is also available on the Center's energy webpage.