Becoming a global hydrogen hub

September 2020

UNIVERSITY of HOUSTON
UH ENERGY

CENTER FOR HOUSTON'S FUTURE

UNIVERSITY of HOUSTON
C. T. BAUER COLLEGE of BUSINESS
Gutierrez Energy Management Institute

Agenda

Background: from energy capital to energy transition capital of the world

Executive Summary: the role of hydrogen in the future greater Houston energy system

Chapter 1: Activate

- Entering new H2 markets
- Converting Houston's premier system into blue H2
- Launching green H2 chain developments

Chapter 2: Expand

- Scale blue H2 to capture export market opportunities
- Extending green H2 to new markets

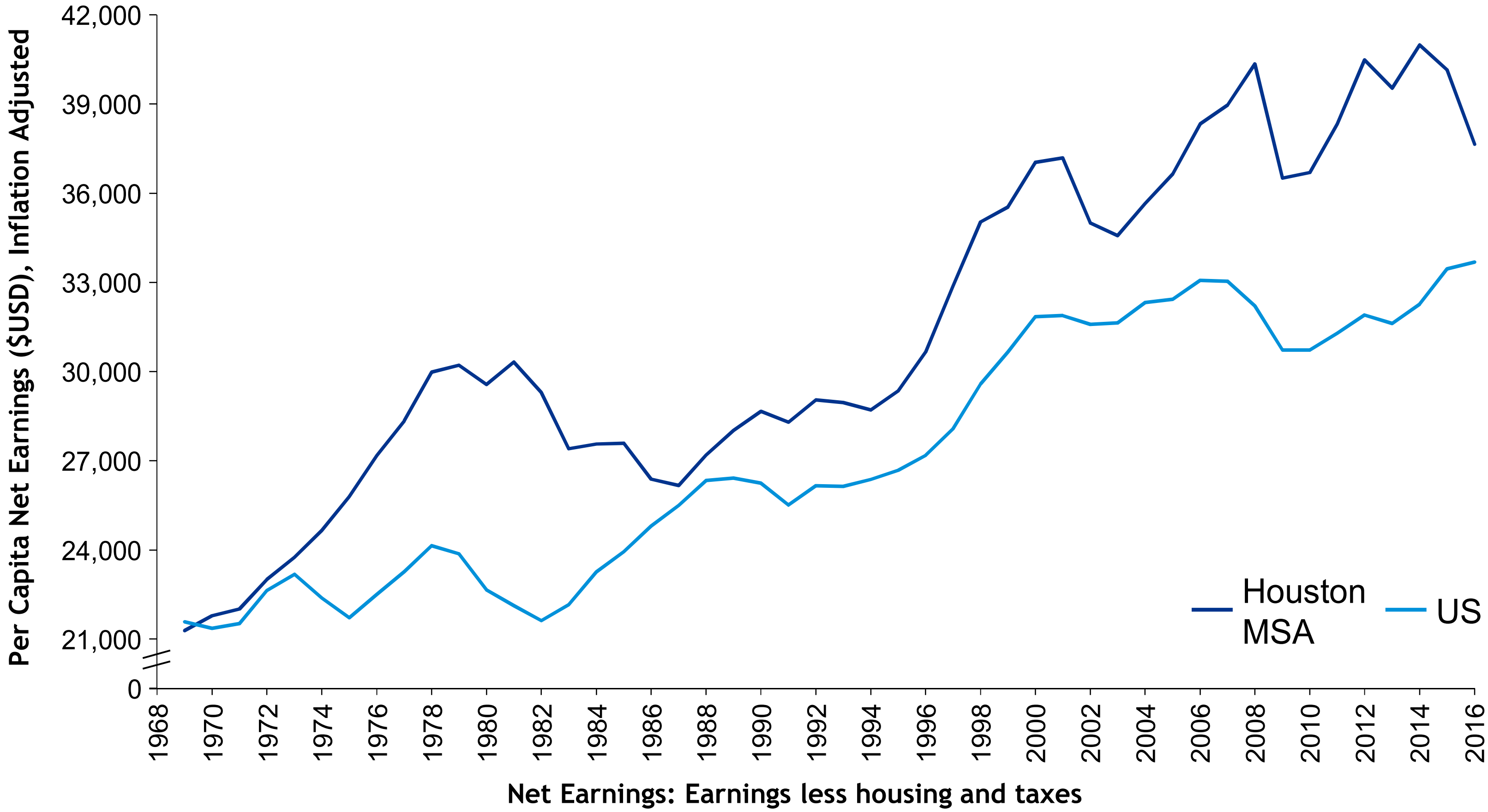
Chapter 3: Rollout

- Blue and green market upside as trends evolve

Chapter 4: Integrated Greater Houston H2 roadmap and next steps

Appendix

Pre-2014 oil price collapse, Houston enjoyed advantaged economic growth vs. peer cities and the overall US economy



Note(s): Per Capita Net Earnings adjusted using US Bureau of Labor Statistics Inflation Calculator
Source(s): US Bureau of Economic Analysis

Upstream oil and gas has been the primary catalyst for Houston's growth advantage

Houston Metropolitan Statistical Area (MSA) and US per capita net earnings drivers

35%

US Economic Growth

- Houston economy tracks overall US economy

35%

Upstream Oil & Gas Industry Growth

- Primary generator of **high multiplier jobs**

30%

Infrastructure & Pro-growth Enablers

- Low housing cost, pro growth policies, low taxes
- Immigration across socio-economic groups

The multiplier effect:

- Economic impacts vary by job type
- Job functions requiring driving inputs from manufacturing, services, construction etc. have higher economic impact

Source(s): Dr. Bill Gilmer from the U of H Institute for Regional Forecasting (model back-tested to 1996)

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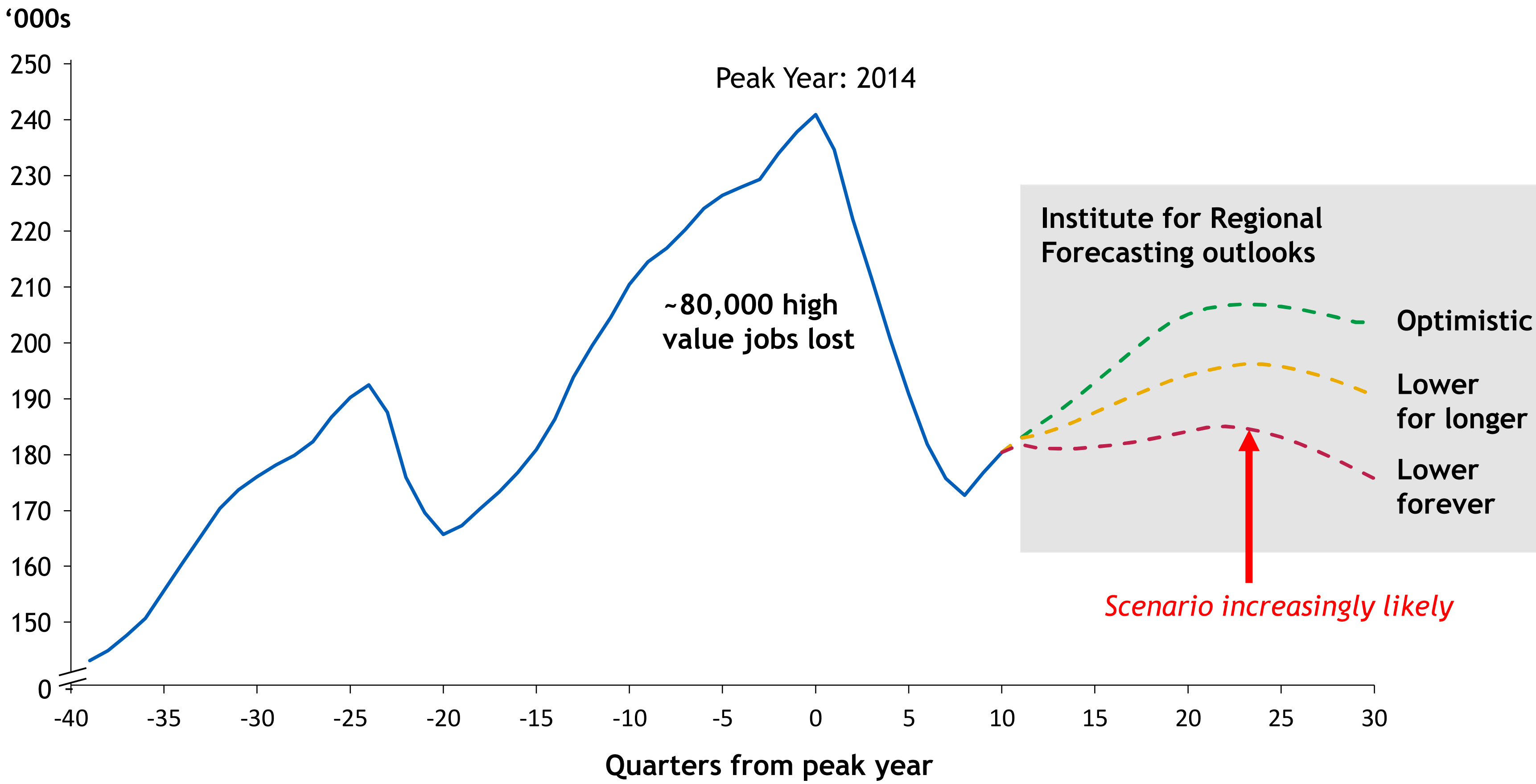
2017 Economical Viability Study

However, it is unlikely Houston can sustain economic outperformance by relying solely on O&G industry growth

Houston MSA oil and gas related jobs versus peak quarter



Note(s): Jobs consist of oil production, oil services, machinery, and fabricated metals – change from SIC to NAICS coding results in classification change
Source(s): US Bureau of Labor Statistics; The Institute for Regional Forecasting

Moving forward, Industry diversification will be required to supplement Houston's O&G base economy

Scenario (Houston GDP growth)	Diversification	Implication
High risk (lag peer cities)	**Limited**	Assuming the oil and gas rebound does not occur and Houston MSA does not diversify, economic performance will lag the general economy and peer cities
Keeping up (match peer cities)	**Selective**	Limited diversification - arguably the current path - even with continued petrochemicals exports and modest oil and gas recovery, will at best leave the Houston MSA in a parity situation with peer cities and the overall US economy
Return to outperformance (outpace peer cities)	**Significant**	Without sustained oil and gas cyclical upside, more significant business diversification will be required to return greater Houston area to prior levels of US and peer city economic outperformance

Sources: US Bureau of Labor Statistics, IMPLAN, KPMG

2017 Economical Viability Study

High multiplier sector diversification options exist where Houston has the rights to win, and lead the Energy Transition

High job multiplier sector diversification options:

- Utility scale renewables
- Plastics and Chemicals manufacturing & recycling
- Carbon sequestration and usage center
- Hydrogen hub *(Focus of this study)*
- Data science and technology
- Healthcare manufacturing and R&D

Low carbon leadership opportunities (Utility scale renewables; Plastics and Chemicals manufacturing & recycling; Carbon sequestration and usage center; Hydrogen hub)

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Appendix

Our project sought to develop a customized roadmap to enter and scale clean H2 in greater Houston

Project scope & Objectives

- Summarize how Houston area can leverage its unique assets to enter clean blue and green H2 production
- Identify and prioritize the most advantaged H2 end markets to create new blue and green chains
- Develop a phased roadmap to scale the use of clean H2 and a view/vision of H2 in the Houston energy system
- Identify next steps and key collaborators to operationalize advantaged blue and green H2 chains

Key contributors

Key Findings

- **Global decarbonization momentum is growing,** catalyzing substantial **global H2 market expansion of $800 billion** by 2050, as part of **H2 gas plus related technologies market of $2.5 trillion**
- **The Houston area is poised to lead H2's growth in the energy system**
  - World leading existing H2 system positioned to bring H2 to market, at-scale, quickly
  - Opportunity to create a green H2 industry over time by leveraging significant low cost renewable power and storage synergies
- **There are four immediate initiatives to launch Houston area blue and green H2 market opportunities**:
  - Launch heavy trucking
  - Clean existing H2 system (via CCUS)
  - Exploit seasonal storage
  - Pilot long duration storage
- **Long term, Houston has opportunity to become a local, national, and global flywheel for H2 penetration into heavy industrial markets**
- **Kick starting the H2 economy** and exploiting Houston's advantages to globalize its leadership in H2, becoming a **global H2 hub,** will require **targeted policy and funding commitments** be made in **short order**

Notes: CCUS refers to carbon capture, usage, and storage

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

Examples of momentum for decarbonization

Why Hydrogen?

Versatile
- Carrier
- Process heat
- Power conversion

Clean
- Burning
- Fuel cell

Abundant, but
- Plentiful
- Must manufacture transport, ship

Unique hydrogen roles in decarbonization

Increasing electrification potential ←

- Light transport
- Short term power storage
- Light industry
- Residential heating/cooling

- Heavy transport
- Power backup, long-term storage
- Refining / chemicals feedstocks (no option)
- Steel and cement, heavy industry process heat

→ **Increasing hydrogen potential**

For example, Germany issued a decarbonization strategy featuring electrification, renewables, and hydrogen

Guiding principles

1 Continue driving electrification of applicable markets, in parallel to accelerating renewable grid penetration

- Providing clean power to all existing uses, and expanding into adjacent markets (e.g., light transportation and industry, home/building heating)

2 Prioritize renewable power to displace fossil power over green H2 production

- GHG impact of fossil power displacement higher priority than producing green H2 due to conversion inefficiencies and substantial power requirements

3 Accelerate blue H2 to address hard to decarbonize sectors (e.g., steel, refining, H2 chemical feedstock, heavy industry and transport)

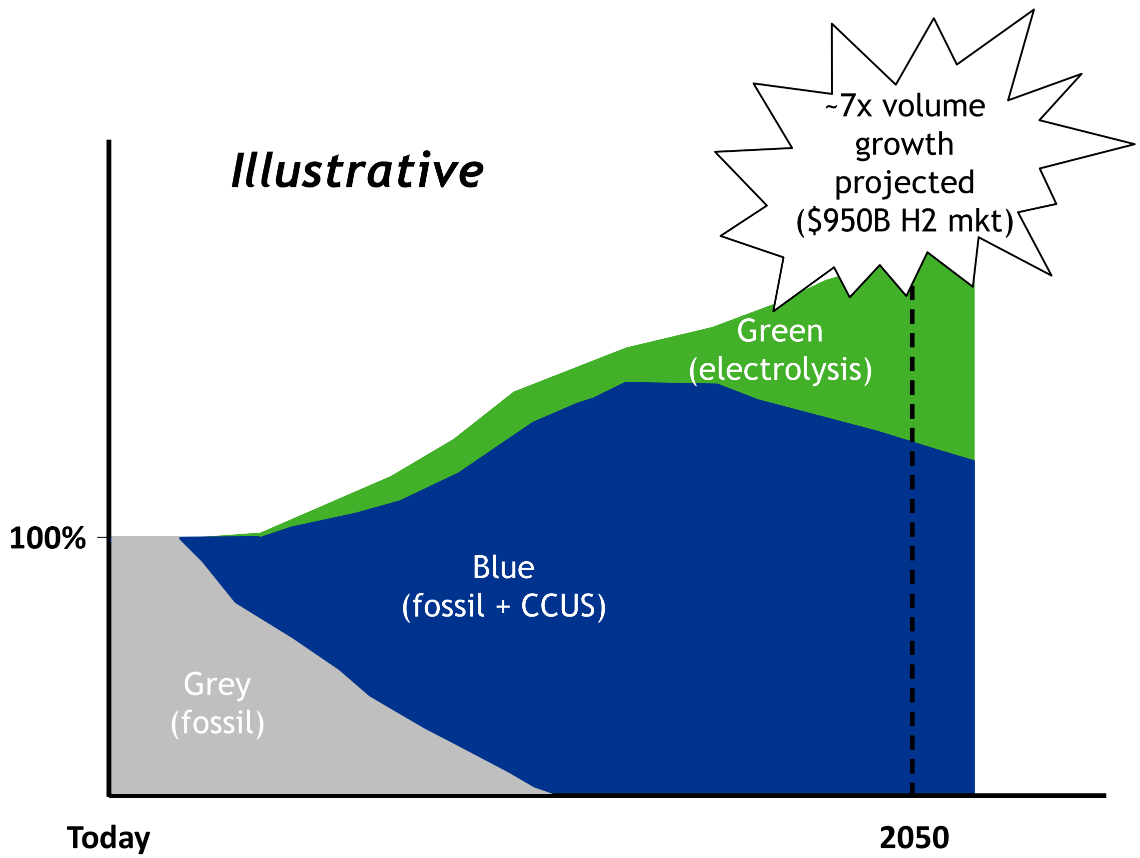
- Blue H2 can be manufactured at scale and cost competitively now, while green H2 is further developed

4 Find advantaged entry points and build scale in green H2 and wind power

- Leverage renewable curtailment pricing to support H2 storage, enabling increased renewable grid penetration
- Develop offshore wind supply chain and synergize with H2 as transmission medium

A general pattern is emerging for progressing the clean H2 economy (grey to blue, expand blue, while nurturing green)

Hydrogen demand and mix over time



Source: Barclays, HSBC, Hydrogen Council

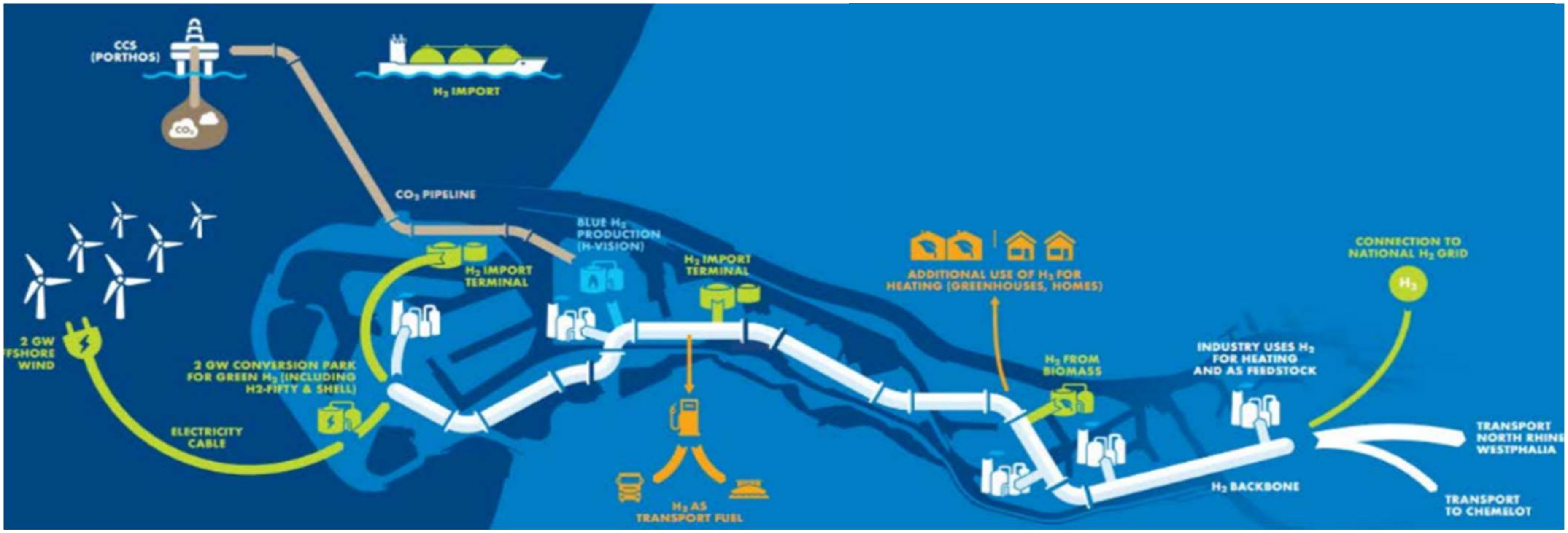
Localized Drivers

- Goals: 2050 net zero or similar
- Funding: Carbon fees or other
- Leverageable assets (blue)
  - H2 system
  - At-scale CCUS hub
- Leverageable assets (green)
  - Geologic storage
  - Low power prices

Cross cutting Enablers

- Cost and supply chain improvements
  - Electrolyzers
  - Renewables
- H2 and renewable synergies

Rotterdam is transforming from a global O&G to hydrogen hub, following this grey to blue to green pattern



From – energy hub of today…

- Refining hub with distillation capacity of 1.2MBOE/D
- European gateway and logistics point, where energy commodities arrive and are distributed
- Global market clearing point (e.g., refined products, bunker fuel)

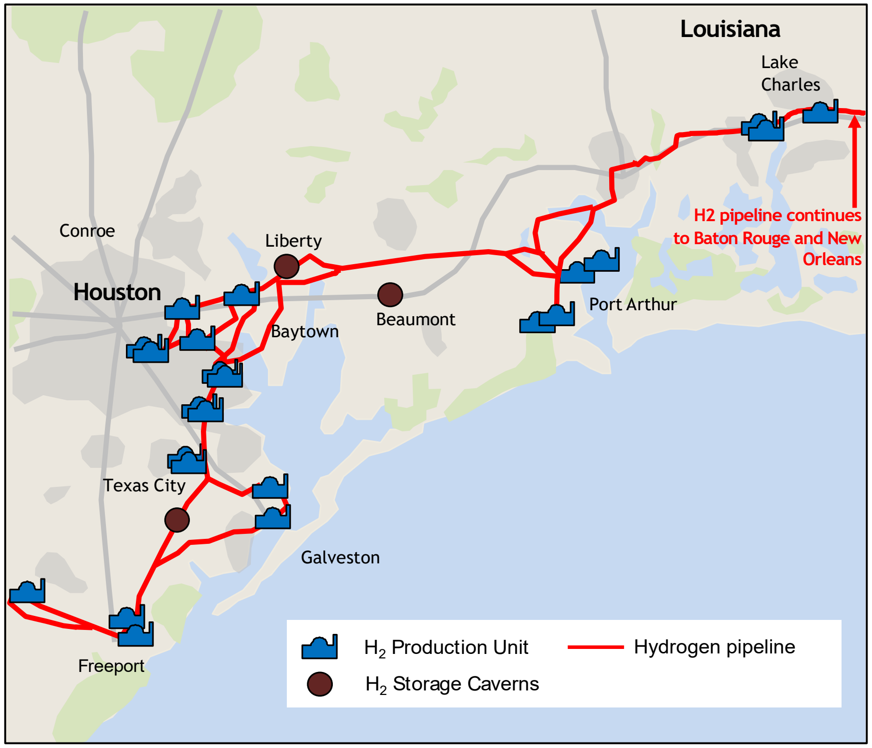
To – energy hub of tomorrow…

- Clean (blue and green) H2 production hub with integrated system
- H2 gateway and logistics point with Northwest Europe, where 20MMt tons pass through annually
- Trading market for H2 with pricing transparency

Source: Rotterdam Vision

The Houston area holds an anchor position in a world class H2 system, enabling rapid, scale access to new markets

Existing hydrogen system in the Gulf Coast area



*** Existing H2 system could leverage in-place CCUS assets (e.g., Denbury pipeline) to readily add and scale CCUS to convert grey to blue H2*

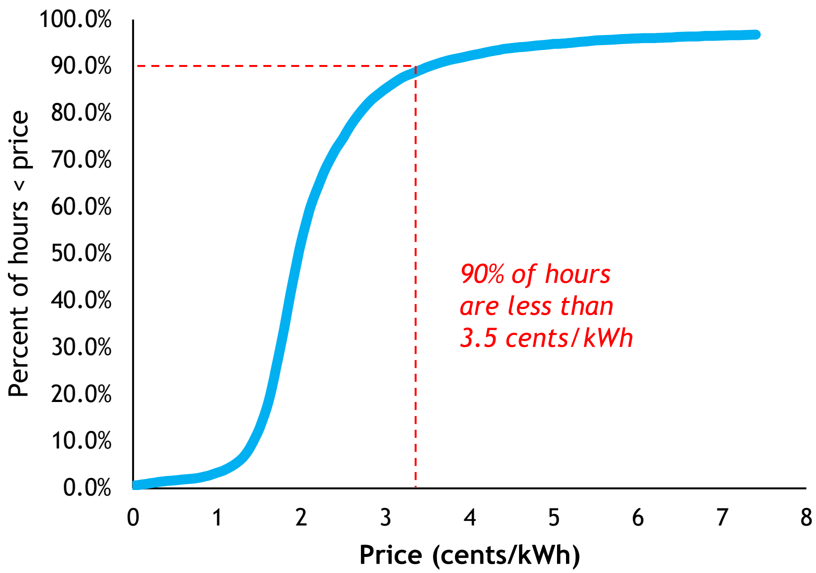
TX Gulf Coast H2 system advantages[1,2,3]

- Over 900 miles H2 pipelines (56% of US; 32% of global)
- ~3.4MMt of H2 produced annually largely through steam methane reformation (34% of US; 8.5x Rotterdam)
- 48 H2 production plants
- World's largest storage caverns for H2; adjacent to H2 network

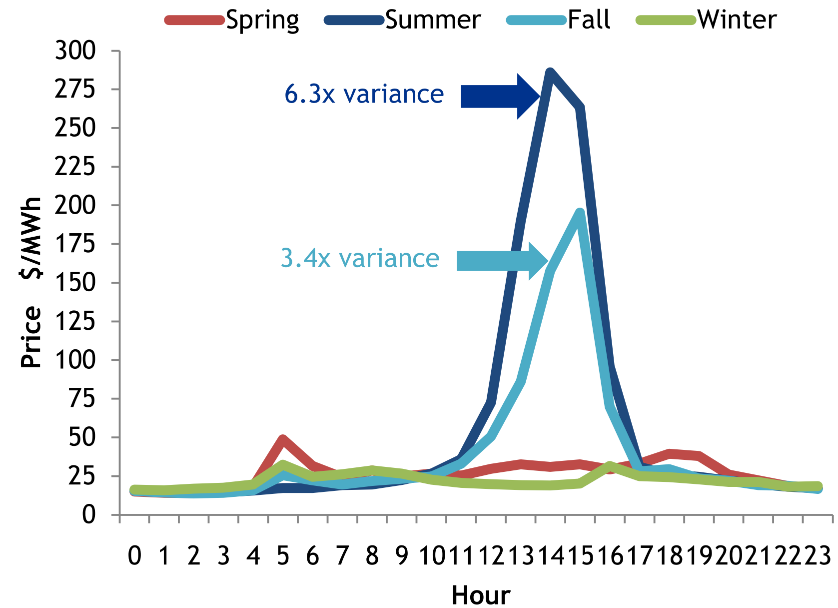
Notes: (1) Houston MSA defined Austin, Brazoria, Chambers, Fort Bend, Galveston, Harris, Liberty, Montgomery and Waller counties; (2) TX Gulf Coast includes a region from Corpus Christi, TX to Lake Charles, LA; (3) Number of global H2 plants estimated by dividing global H2 production by US avg. production per H2 plant (52k tons H2 / year)
Source: H2Tools; USDOT PHMSA - National Pipeline Mapping System; Seeking Alpha; Office of US Energy Efficiency & Renewable Energy; Hydrogen Europe

Additionally, TX has multiple advantages that could improve green H2 economics, supporting a green industry build out

Houston wholesale price duration curve, 2019



Average Houston hub wholesale power price, 2019[1]



- Low cost generation and competitive market structure
- Extensive and growing renewables (#1 wind, #2 solar by '25), increasing long-duration storage role
- High seasonal price differentials, coupled with low cost storage, enhances storage economics

Notes: (1) variance for high and low prices is calculated based on summer and fall modified off peak hours (11am to 5 pm)
Source: ERCOT, S&P Platts

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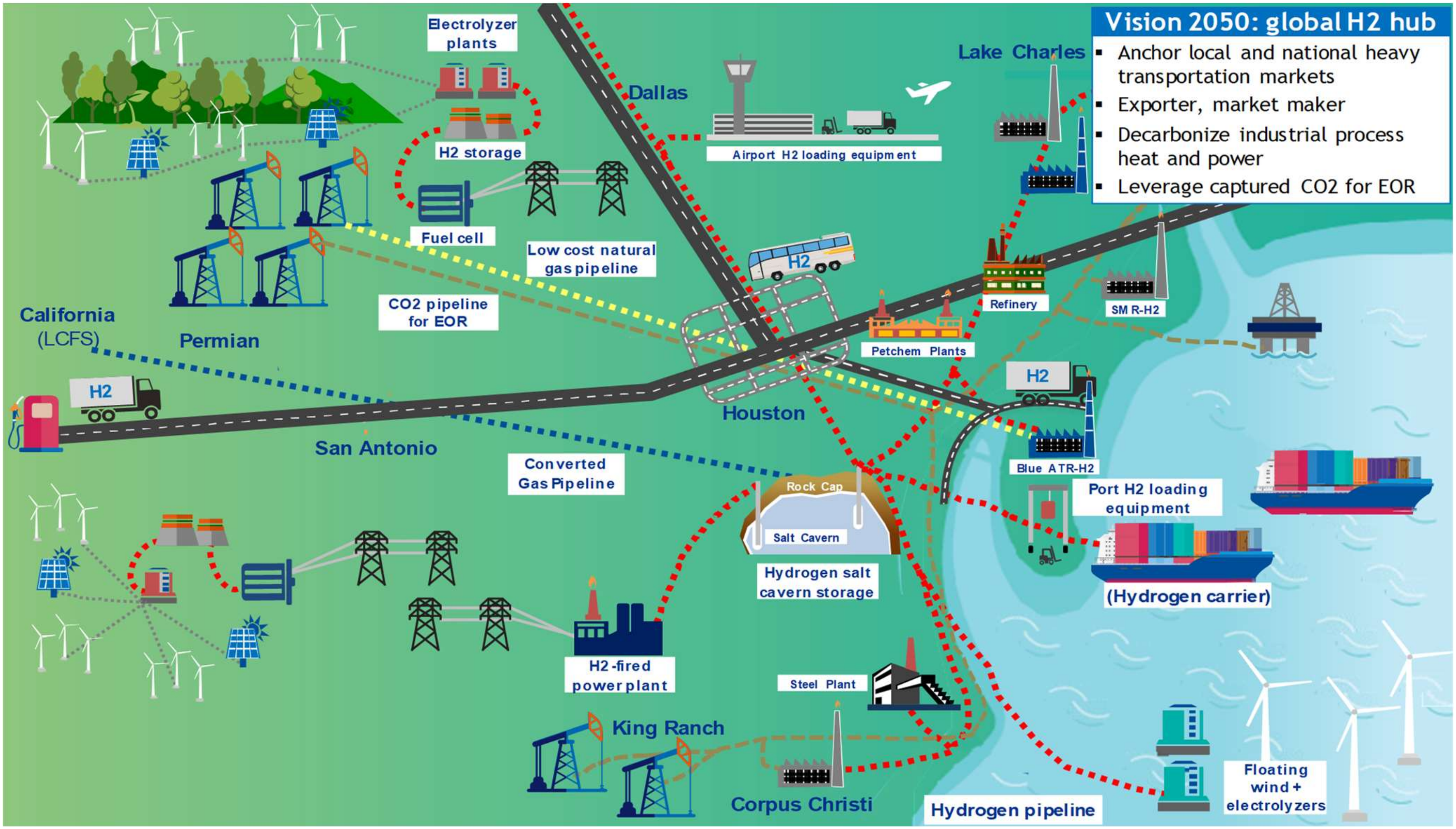
Potential Houston '2050 vision': local, national, and global flywheel for H2 penetration into heavy industrial markets



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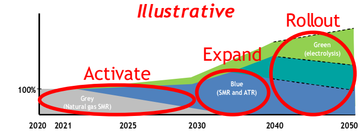
A potential customized path for Houston provides a phased approach scale clean hydrogen

Houston hydrogen production mix over time



Global hydrogen hub

	Activate 2020 - 2030	Expand 2030 - 2040	Rollout 2040 - 2050?
Production	• CCUS for priority H2 plants (8) • H2 seasonal and long duration storage pilots	• CCUS for remaining H2 plants (40) • Expand blue for export • Extend green synergistically with renewables	• Scale offshore wind and electrolyzer production
Markets	• Heavy trucking pilots (grey H2) • Expand H2 trucking infrastructure	• Export to advantaged markets (e.g. CA for LCFS) • H2 for transit buses; decarbonize gas-fired power	• Use low cost H2 to decarbonize industrial processes
Investment[1,2]	**$600M - $900M**	**$1,700M - $8,500M**	**TBD**

Increasing investment and policy support required

Grey H2 — Blue H2 — Green H2 — Potential for blue/green H2

Benefits

- Capture new H2 markets created globally
- Further diversify Houston economy and create new jobs
- Progress decarbonization (15.4 Mt CO/year reduced by 2050)
- De-risk / mitigate carbon impact of heritage refining and petchem industry

Notes: (1) Activate costs assume 50% stretch case investment; (2) 5x stretch case added to investment for expand phase to account for excluded costs (i.e., new blue plants, new green storage applications,); (3) Reduction in Co2 emissions refers to converting trucking to blue H2, buses to green H2, and adding CCUS to existing H2 plants

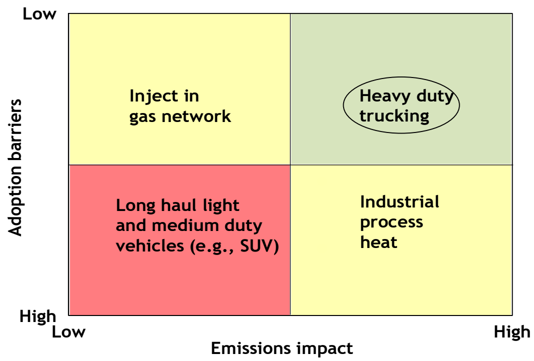
Activating the plan to achieve global H2 leadership centers on four immediate initiatives, with targeted policy/funding

Activate

Launch heavy trucking

- Leveraging existing coalitions, assemble group(s) and select / optimize the most attractive market(s) to enter
- Develop roadmap from activate through rollout

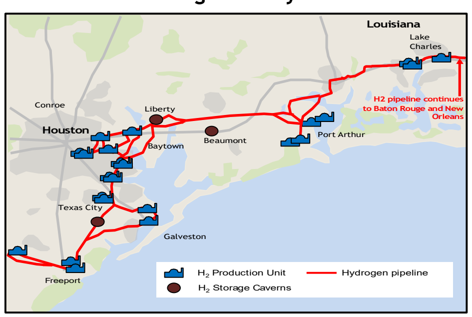
Prioritization of blue markets



Clean grey system

- Assemble coalition
- Develop a prioritized phased plan to couple the high-volume existing H2 system with existing and extended CCUS systems

Existing TX H2 system

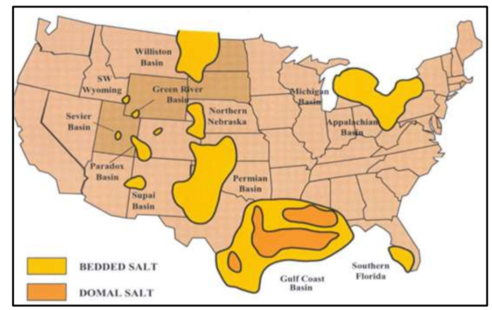


Activate

Exploit seasonal storage

- Conduct feasibility study (e.g., GTI DOE study) of most cost effective options to leverage Houston's utility scale, low-cost salt caverns for H2 storage

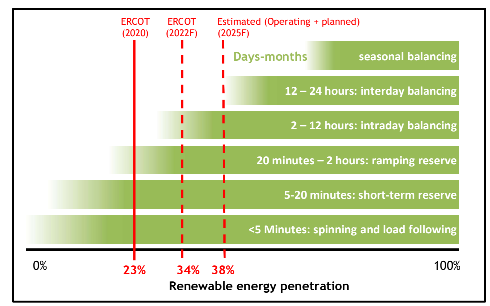
US salt cavern storage



Pilot long duration H2 storage

- PUC to assess H2 storage fit with substantial and growing renewables
- Evaluate funding/policy required to enable maximizing renewable value and ensuring reliability

Storage required by renewable penetration



Policy and funding

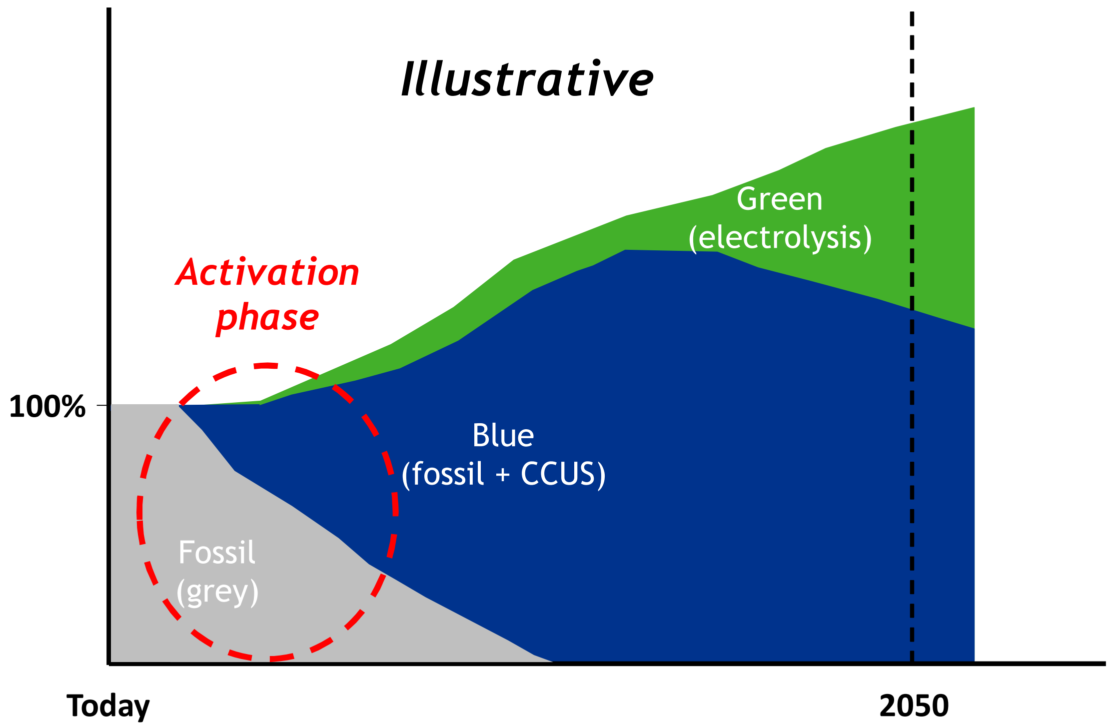
- Assemble group (e.g., state and federal attorneys, policy makers) to shape potential policy support for TX clean H2 economy
- Develop targeted policy / funding approach, which unleashes new attractive market opportunities, near and longer term
  - Critical to establish market opportunity for H2 and address looming impact of low carbon future on TX economy

Notes: (1) PUC refers to Public Utility Commission

Agenda

In the activation phase, one priority is to leverage and clean the existing grey system (and the other to initiate green)

Hydrogen demand and mix over time



Grey to blue activation phase

Initial new market expansion for blue H2 in Houston area

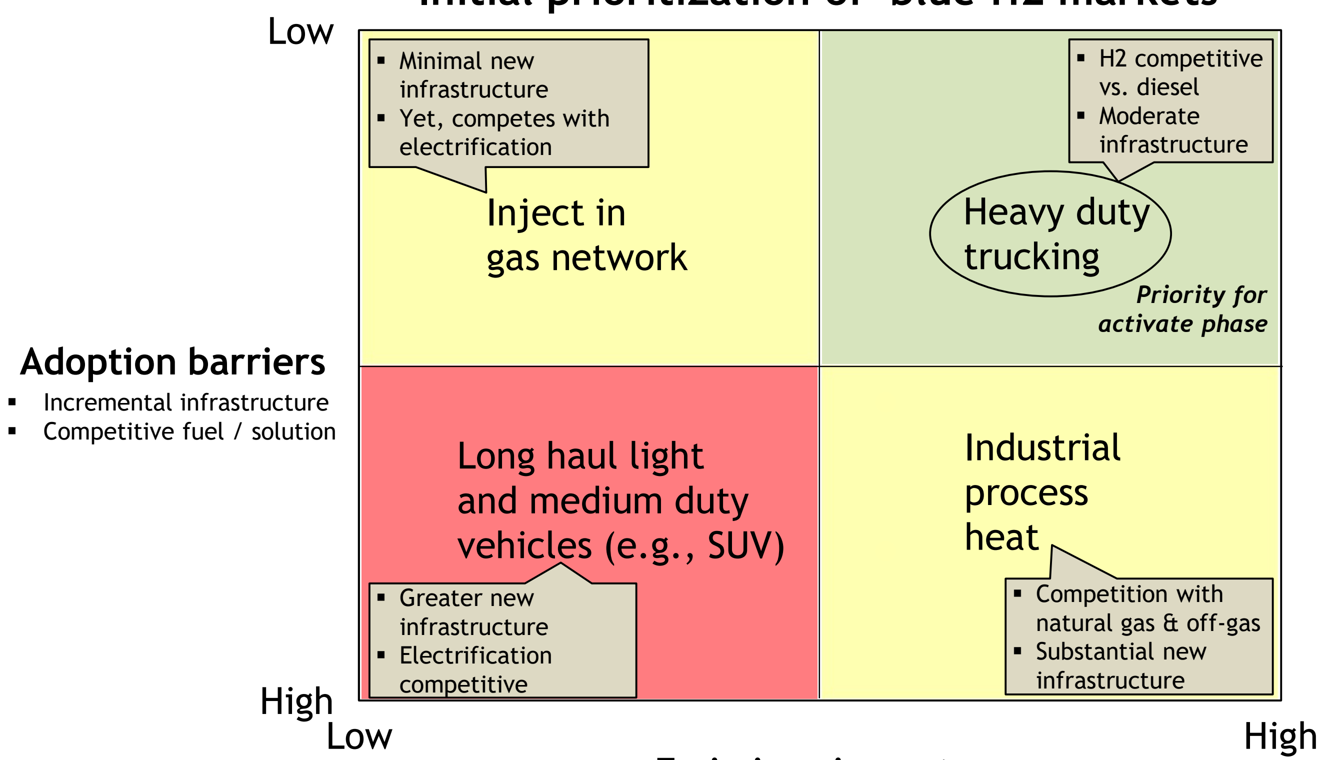
- **A** Prioritization of potential new markets for H2…
- **B** …shows heavy trucking provides priority near term opportunity

Clean existing H2 production

- **C** Integrating CCUS into existing H2 system required to be global leader in clean H2
- **D** Other regions demonstrate scalable CCUS around initial anchor point
- **E** Potentially unique opportunity to activate CCUS at low cost in Houston area

New markets were prioritized based on relative adoption barriers (or advantages) and emissions impacts

Initial prioritization of blue H2 markets



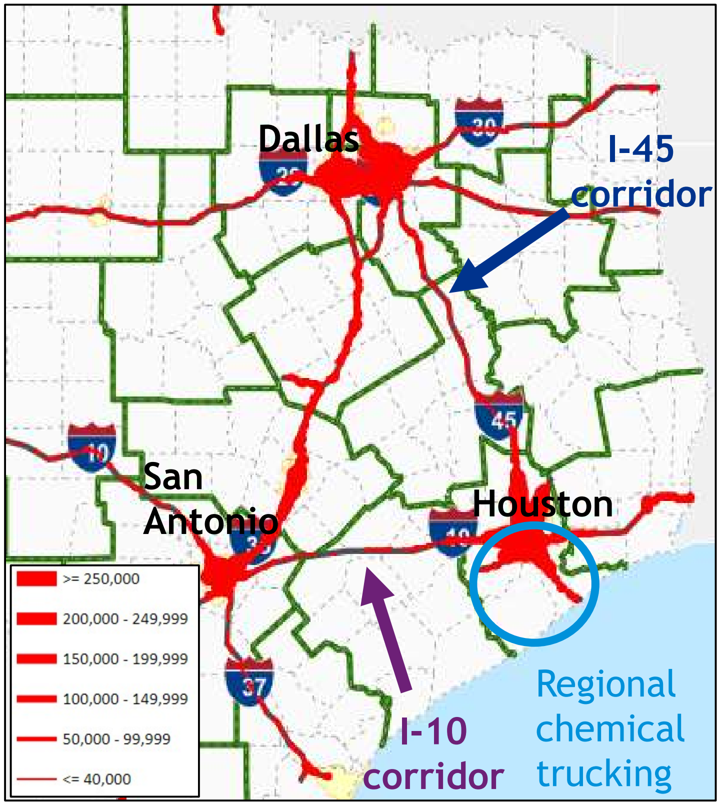
"We see heavy hauling of freight as kind of like an anchor tenant in the hydrogen shopping mall."

\- Program Lead,
Canadian Energy Systems Initiative

Notes: (1) Access to CA Transportation / LCFS via addressed in Expand phase; (2) Seasonal / long duration storage addressed as part of green H2 chain
Sources: S&P Platts

B There are several local and regional heavy trucking markets which offer potential demonstration/entry points

Texas truck traffic, 2018



***Truck markets are focused on those involving the Houston area. Assessing viability of H2 trucks in other TX truck markets (e.g., I-35) is out of scope for this study.*

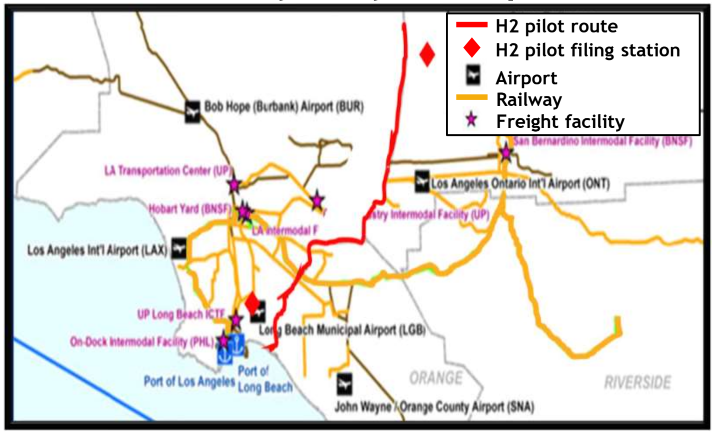
Houston truck markets: overview and pro's/con's of H2 entry

I - 45 (Dallas - Houston)	**Heavy Duty daily truck count:** 4,819 **Duty cycle:** long-haul trucking **Pro's for entering with H2** • Existing stakeholder coalition in place (NTCOG+) • Potential to link to Dallas/central US distribution hub, and on to I70 (transnational corridor) **Con's for entering with H2** • Houston to Dallas link not sufficient stand-alone
I - 10 (San Antonio - Houston)	**Heavy Duty daily truck count:** 1,557 **Duty cycle:** long-haul trucking **Pro's for entering with H2** • Foundation to potential I-10 corridor- east and west • Synergies with P/L to tap Calif LCFS market • Potential to leverage existing H2 pipeline from Baton Rouge to Houston (and Houston to LA) **Con's for entering with H2** • Less local traffic than Port and I-45
Regional chemical trucking (Houston ship channel)	**Heavy duty truck count:** 40,000 (80% chemicals export) **Duty cycle:** return to base **Pro's for entering with H2** • Higher payload capacity and torque vs. BEV trucks • Potential easier demonstration project **Con's for entering with H2** • BEV trucks may be advantaged for shorter, return to base ship channel truck trips

Notes: (1) Number of trucks determined by dividing ton-miles transported between cities by max truck payload
Source: NHTSA.gov commercial mdhd trucks; Interview with Chad Burke from Economic Alliance for Houston Port 16Jul20; Oak Ridge National Lab – FAF Tool; TxDOT

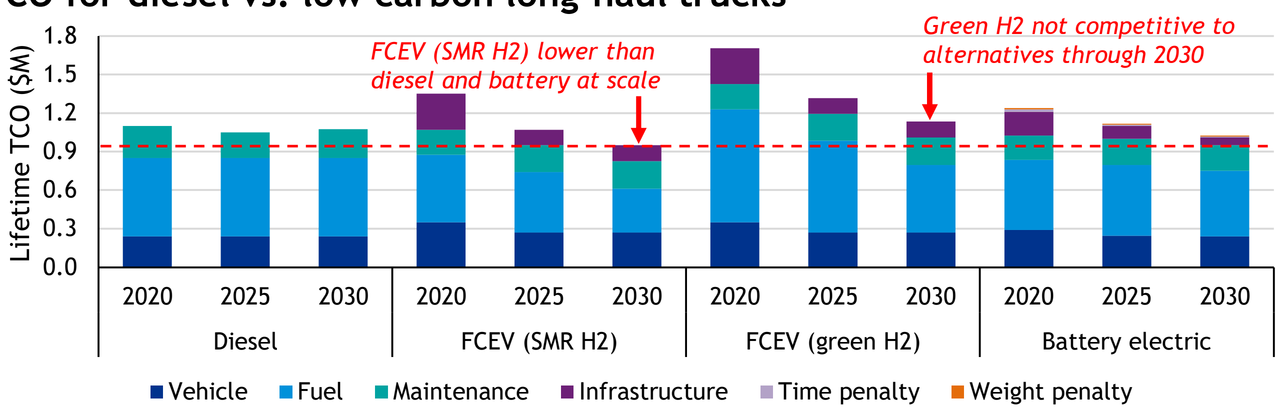
B H2 heavy trucking pilots are underway in the LA port area, and studies indicate advantages vs. with diesel and electric

Port of LA Heavy-Duty truck pilot



- Consortium of public and private (Port of LA, Shell, Toyota, Kenworth) stakeholders convened to test viability of using hydrogen in heavy duty trucks to reduce emissions in port drayage activities
- Pilot involves 10 HD FCEV trucks and 2 filing stations, costing $82.5M with and funding split between CA and private players

TCO for diesel vs. low carbon long-haul trucks[1,2,3,4]

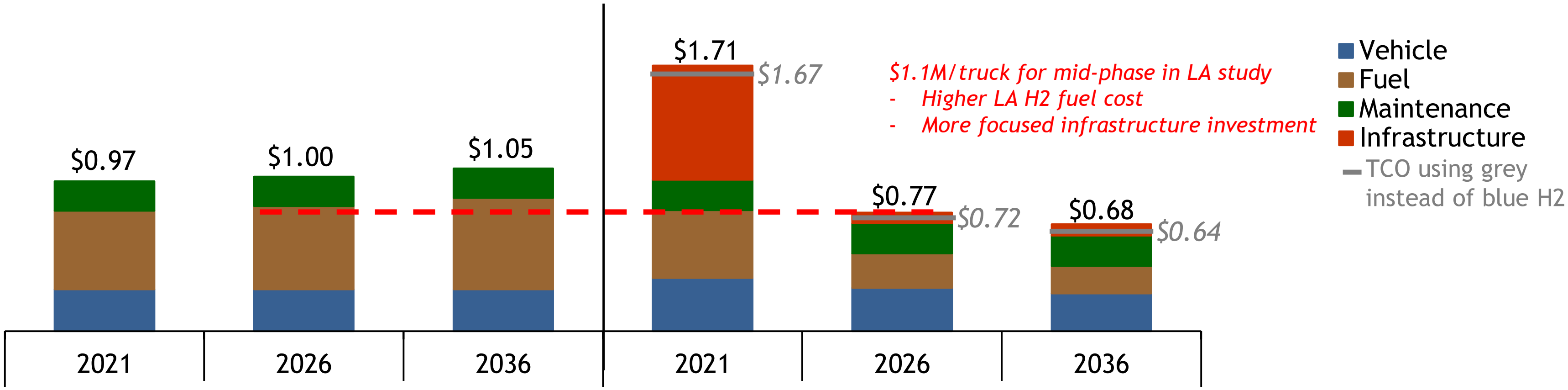


- Lower H2 (SMR) TCO driven by:
  - Low H2 (SMR) cost
  - Increasing diesel costs projected
  - High returns to scale on infrastructure

Notes: (1) ICCT study based on LA Port area with 100, 1,000, and 10,000 trucks deployed in 2020, 2025, and 2030; (3) Time and weight penalty applied to BEV trucks; (4) H2 supplied via tube trailer
Source: ICCT

Preliminary indications are H2 is also advantaged locally. Using grey H2 can kick start the market while reducing emissions

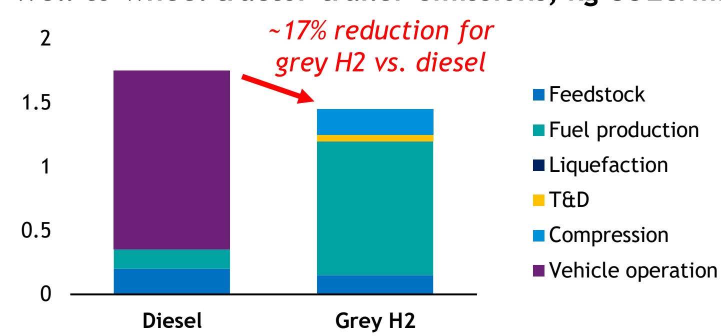
Total Cost of Ownership, diesel and H2 HDVs on I-45, \$M/truck[1,2]



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

Well-to-wheel tractor trailer emissions, kg CO2e/mile



Notes: (1) 115,620 annual miles driven; (2) station utilization: expand: 50%, rollout: 60% (3) pilot, expand and rollout phases last 10 yrs ea.; (4) YoY H2 truck capex reduction follows three phases (4%: '20-'25, 2.1%: '25-'30, 0.6% ea. yr. afterward)
Source: ANL: HDSRAM, EIA, KPMG analysis, ICCT: Infrastructure needs and costs for zero-emission trucks

B

Several next steps are required to optimize entering I-45 and to evaluate the feasibility of entering other corridors

Markets	Potential next steps
I - 45 *(Dallas - Houston)*	▪ Continue progressing NCTCOG led ZEV initiative focused on I-45 corridor plan (including Dallas – Houston) – Consider adding midstream players to discuss pipeline and rights of way options as part of I-45 plan (to capture cost, time to market, and volume H2 supply advantages) – Examine synergies with I70; exploiting Dallas role as central US distribution hub/crossroads
I - 10 *(San Antonio - Houston)*	▪ Assemble coalition of long haul heavy trucking stakeholders involved across the freight route from San Antonio to Houston to Baton Rouge ▪ Examine synergies with P/L (greenfield or repurpose existing) along I10 corridor to tap LCFS incentive in CA and support I10 heavy trucking corridor ▪ Develop a detailed roadmap from entry to scale; evaluate funding required and available (e.g., TERP)
Regional chemical trucking *(Houston ship channel)*	▪ Assemble coalition of regional chemical trucking stakeholders – Example stakeholders: chemical co's with decarbonization objectives, OEMS, industrial gas providers, CCUS providers, station operators ▪ Assess feasibility of enabling heavy trucking with H2, hybrid H2/battery, and if H2 is viable, develop a detailed roadmap from entry to scale ▪ Evaluate funding required and available (e.g., TERP)

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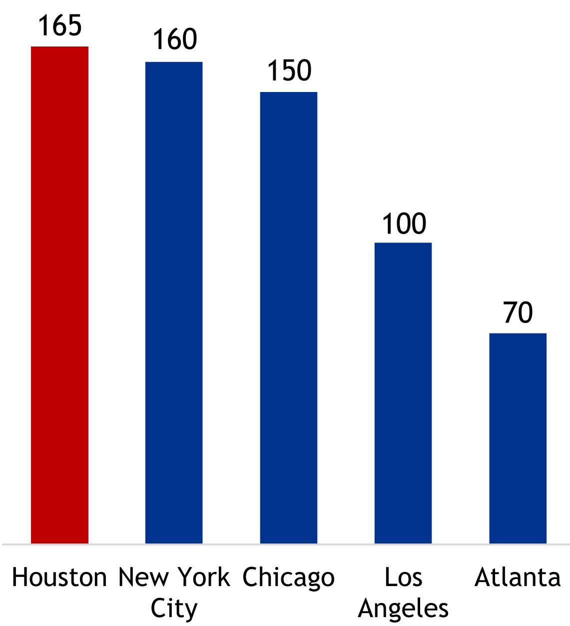
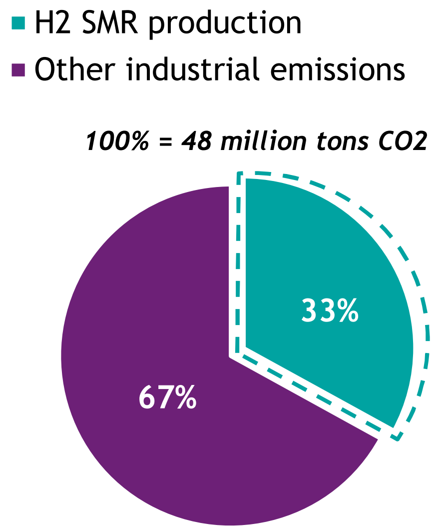
Appendix

A critical enabler for Houston to lead in the low carbon era is to decarbonize its existing grey H2 system

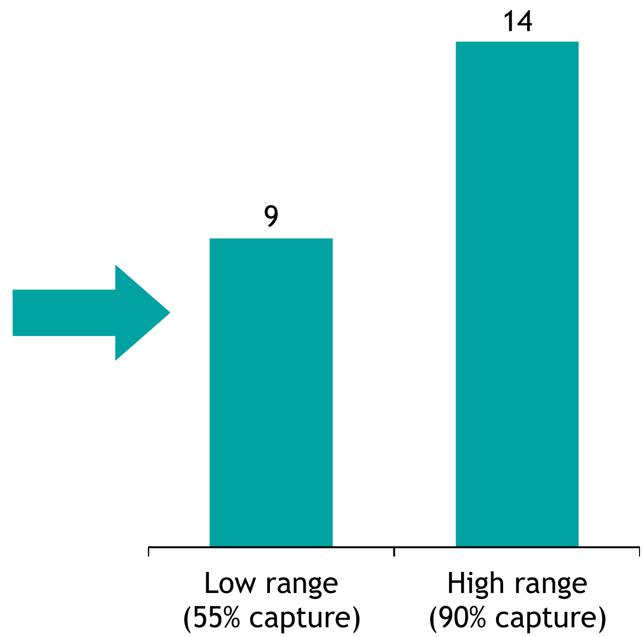
Peer cities, annual million metric tons GHG emissions



Mix of Houston MSA annual industrial CO2 emission sources[1,2]



Potential annual emissions captured by installing CCUS on H2 plants, Mt CO2[3]

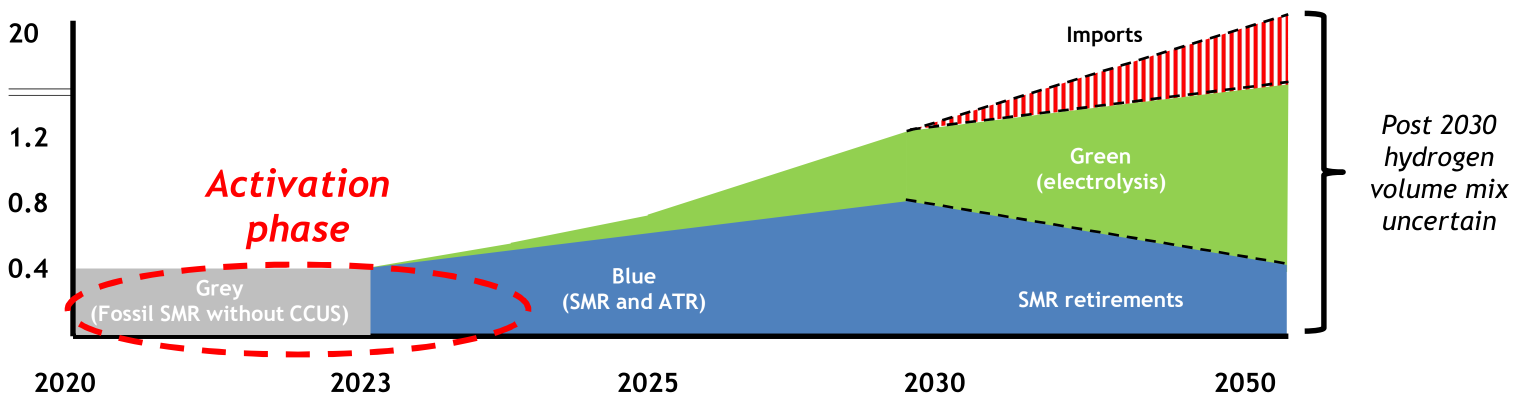


***Range based on IEA GHG study of CO2 captured at SMR H2 plants*

Notes: (1) H2 emissions based on ratio of CO2 emitted per kg H2 produced; (2) SMR CO2 emissions in 2016, other emissions in 2014; (3) Low/high range based on 55% and 90% CO2 by adding CCUS
Sources: US EPA Greenhouse Gas Reporting Program (GHGRP); Environmental Science & Technology; H2tools; US DOE , Denbury, DOE, GRP Capital

For example, Rotterdam's near-term focus is converting its grey H2 to blue through the Porthos offshore CCUS project

Hydrogen production mix (illustrative)[1,2]



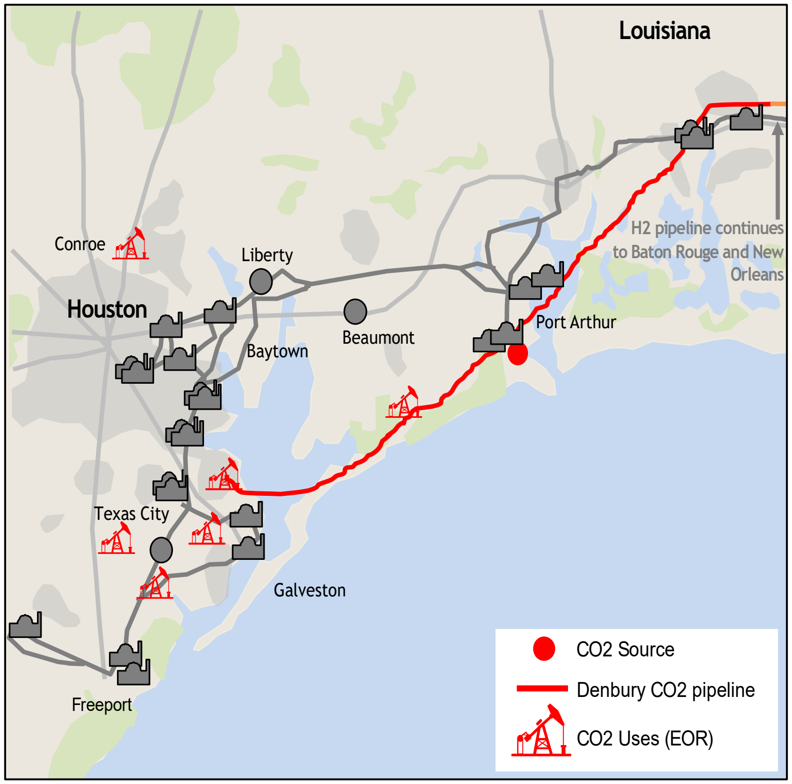
Timeline[3,4]					
Production		Convert grey H2 system to blue (Porthos) and initiate green (Shell) 2023	Blue H2 produced via ATR and expand green (BP) 2025	CCUS infrastructure built on with H-backbone 2030	Green H2 production expanded in electrolyzer park 2050
Market	2021	2023 Blue for industrial feedstock and green for refining feedstock	2025 Blue for industrial processes and green for refining feedstock	2030 H2 market emerges with H2 imported and transported inland	2050 20 MMt of hydrogen passes through the port annually
CO2 tax	$35/ton takes effect	Increases to $57-$63/ton	Increases to $83-$95/ton	Increases to $147-$176/ton	

- ***Port of Rotterdam becomes a trading hub for NW Europe as demand for cleaner energy increases***
- ***Funding provided by mix of public and private investments***

Notes: (1) SMR refers to H2 produced with steam methane formation with CCUS; (2) ATR refers to Autothermal Reforming; (3) Carbon tax increases linearly; (4) Exchange rate of 1.17 USD = 1 euro
Source: Rotterdam Vision; H-Vision Fact Sheet; Porthos Fact Sheet; Netherlands National Climate Agreement

E Leveraging existing CCUS infrastructure and prioritizing H2 plants can start Houston on a path to realizing its substantial blue potential

Existing H2 and CCUS systems in TX-Gulf Coast area



Prioritization of H2 plants to add CCUS in Activate phase

- **Approach and rationale**
  - Use phased approach to capture highest Houston industrial emitters, leveraging existing infrastructure
  - Fill Denbury capacity in Activate phase with top priority H2 plants and natural gas fired power plants
- **H2 plants and emissions reduction**
  - Add CCUS to 8 H2 plants with higher capacity and located within 10 miles of Denbury pipeline
  - Lowers H2 emissions by 5.7 Mt CO/year (35% of CO2 resulting from H2 production)
- **Estimated cost**
  - Each H2 plant estimated at $78.5M to add carbon capture and tie-into Denbury (excludes policy support such as 45Q)

Notes: (1) Houston MSA defined Austin, Brazoria, Chambers, Fort Bend, Galveston, Harris, Liberty, Montgomery and Waller counties; (2) TX Gulf Coast includes a region from Corpus Christi, TX to Lake Charles, LA; (3) Number of global H2 plants estimated by dividing global H2 production by US avg. production per H2 plant (52k tons H2 / year)
Source: H2Tools; USDOT PHMSA - National Pipeline Mapping System; Seeking Alpha; Office of US Energy Efficiency & Renewable Energy; Hydrogen Europe

Agenda

Background: from energy capital to energy transition capital of the world

Executive Summary: the role of hydrogen in the future greater Houston energy system

Chapter 1: Activate

- Entering new H2 markets
- Converting Houston's premier system into blue H2
- Launching green H2 chain developments

Chapter 2: Expand

- Scale blue H2 to capture export market opportunities
- Extending green H2 to new markets

Chapter 3: Rollout

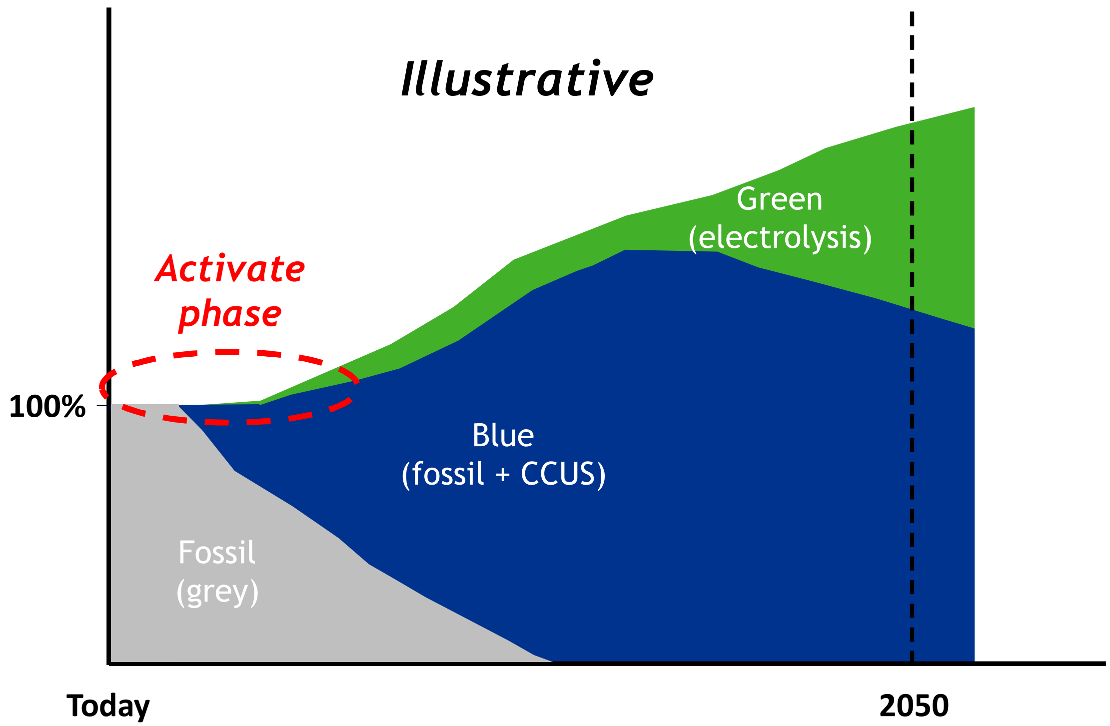
- Blue and green market upside as trends evolve

Chapter 4: Integrated Greater Houston H2 roadmap and next steps

Appendix

We also examined opportunities to activate green H2

Hydrogen demand and mix over time



Green Activation Phase

Houston and ERCOT advantages

- **A** Access to low cost power in TX, a key enabler to green H2

TX renewables penetration driving potential need for long duration storage

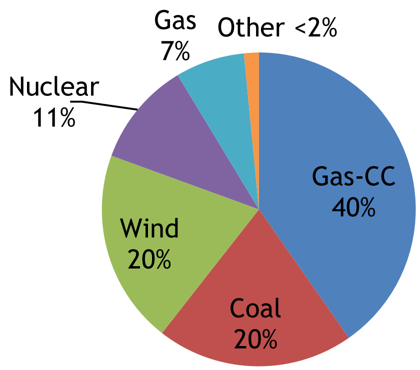
- **B** Growing TX renewables and tapping further low revenue hrs
- **C** Example: NextEra using green H2 to increase solar asset value

Additional enablers and advantages to promote green H2

- **D** Houston's unique advantages - salt caverns and seasonal price differentials
- **E** Example: Delta, UT using similar storage advantages as Houston
- **F** Several policy options could further promote green H2

A The competitive TX market structure supports green H2 economics via a low cost generation mix and low power prices

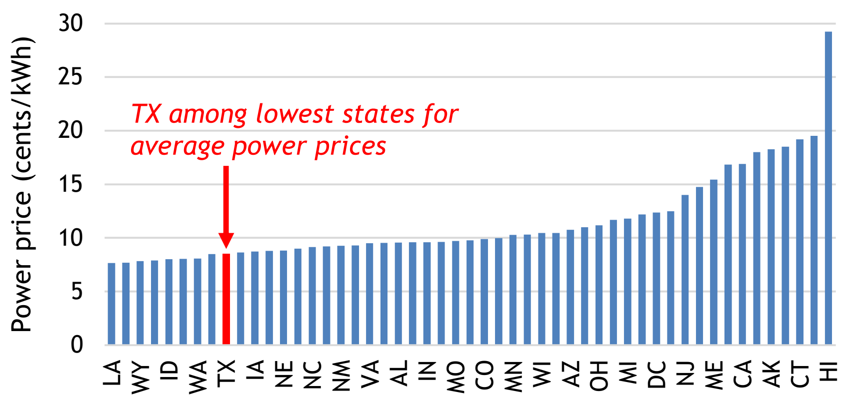
ERCOT electricity generation mix, 2019[1]



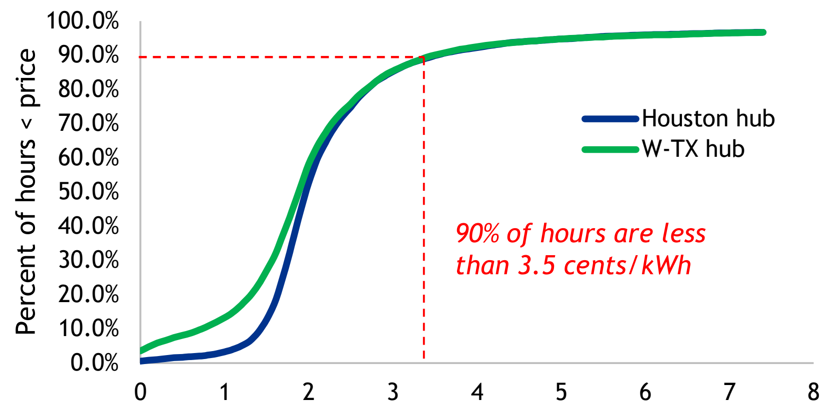
Competitive market structure

- Deregulated energy market
  - Allows customers to choose their supplier
  - Creates retail market competition
- Energy-only wholesale market
  - Generators paid only for energy delivered to market
  - Unique in US as most competitive markets pay generators to provide capacity

Power price by state (cents/kWh)[2]



TX wholesale power prices, 2019

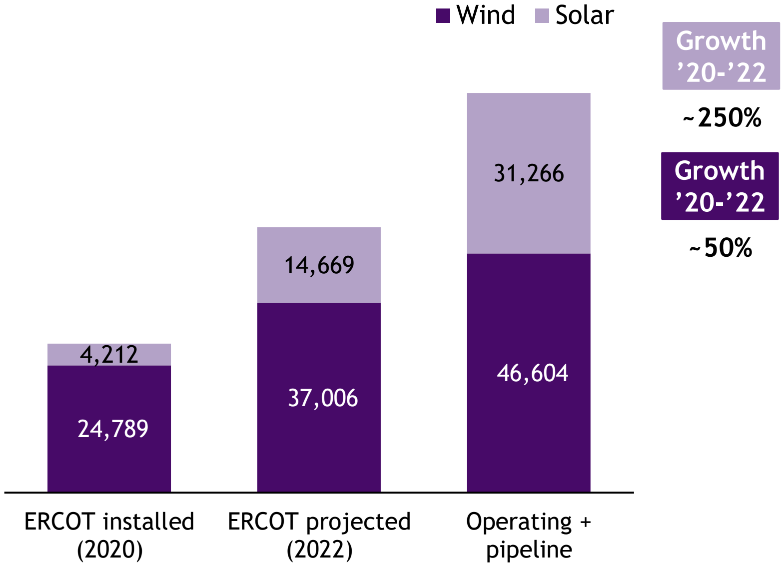


Notes: (1) Other consists of solar, hydro and biomass; (2) Average power price refers to 2018 weighted average sales price across retail, commercial, and industrial sectors
Sources: ERCOT, EIA

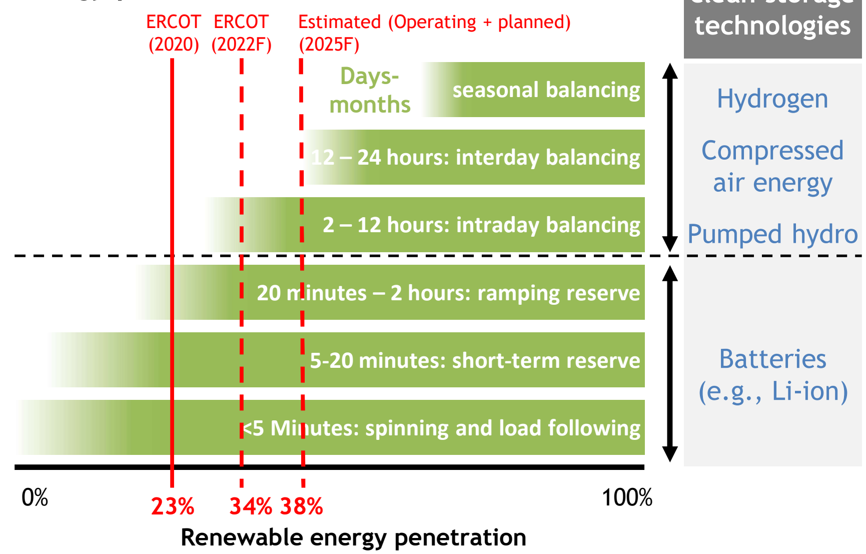
Additional low price hours are expected with wind and solar growth in TX, creating value synergies with storage

B

ERCOT and Texas installed and potential wind and solar capacity, MW[1]



Energy storage requirements vs. renewable energy penetration levels[2,3]



- TX is among top in US in renewable capacity (#1 in wind, projected #2 in solar due to 250% increase over next 5 yrs.)
- Extent of renewables led to 3.1M MWh of wind curtailment in LTM May'20, lowering wind asset revenue
- Significant uptick in projected solar and wind capacity could increase low revenue hours for renewables

- Long duration storage may have a growing role
  - Coupling storage with renewables helps increase revenue hours and asset value
  - Establishing longer duration storage offsets variability introduced with higher levels of renewable penetration

Notes: (1) Pipeline refers to planned projects; (2) 2025F assumes pipeline installed by 2025; (3) 2025F penetration assumes linear penetration given capacity/penetration levels from 2022 and 2022F
Sources: Cleantech Group, Rocky Mountain Breakthrough Batteries, Apex Compressed Air Energy Storage, ERCOT, NREL, Lawrence Berkley National Lab

NextEra, for example, is testing green H2 storage technology by pairing it with a new solar installation

FP&L green H2 production overview

Utilize substantial curtailed renewable power

Power electrolysis plants with low cost renewable power to produce green h2

Blend H2 with natural gas in gas-fired power plant to reduce emissions

***Potential H2 storage mechanism not yet announced*

Project insights

- NextEra has committed to reduce emissions by 100% in 2050
- Led to pilot study to test green H2 feasibility
- **Pilot offers mechanism to improve solar asset value**
  - **Exploit price arbitrage** (produce H2 during low demand hours and use H2 during high demand)
  - **Offset lower revenue hours**
- H2 **reduces emissions** by replacing portion of natural gas in gas fired power plant
- Plan to request funding approval from Florida Public Service Commission ($65M)

Key stakeholders

NEXTera ENERGY

FPL

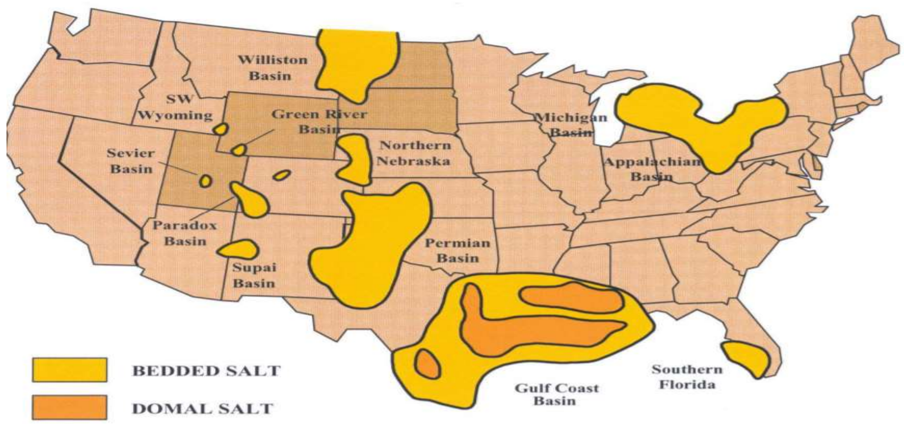
Sources: S&P Global, Green Tech Media, Clean Technica, Rocky Mountain Institute

D Unique scale storage plus high price differentials suggests seasonal storage in the Houston hub be explored

Houston advantage:

Large scale H2 storage caverns

US salt cavern resources

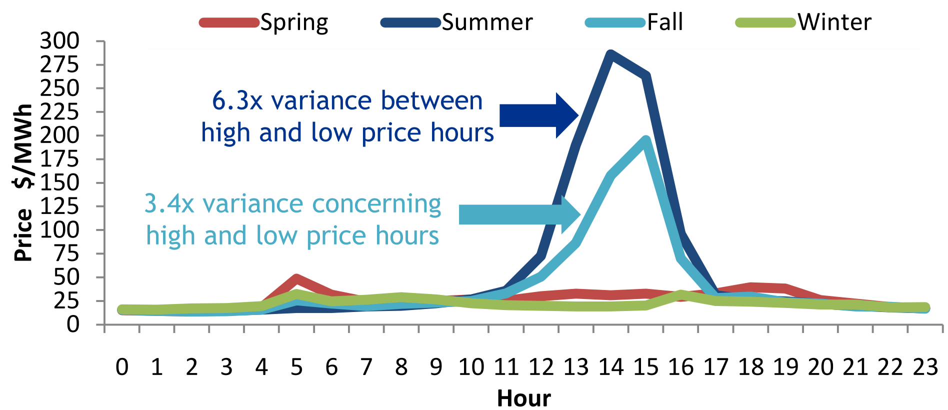


- Houston MSA has three existing utility scale H2 storage facilities developed in salt caverns

Houston advantage:

High seasonal price differences

Average Houston hub wholesale power price, 2019, $/MWh[1]



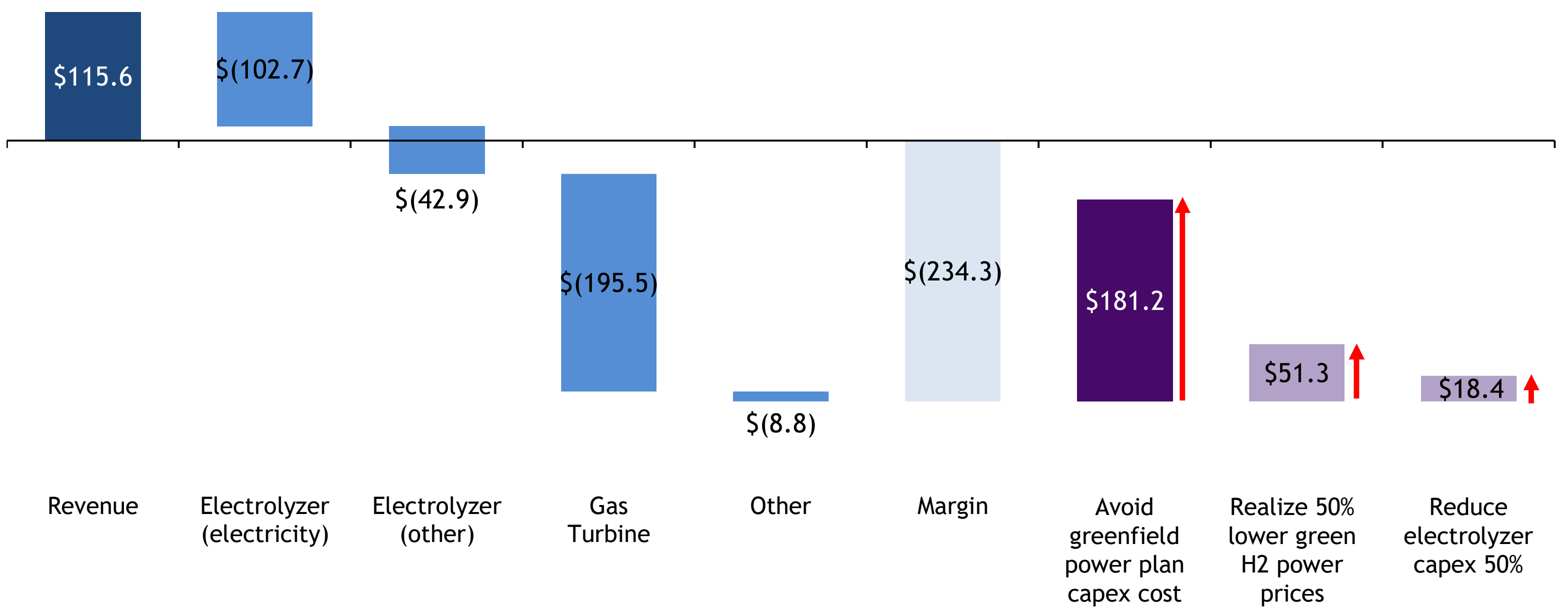
- High seasonal price differentials suggest the potential for long duration storage leveraging H2

Notes: (1) variance for high and low prices is calculated based on summer and fall modified off peak hours (11am to 5 pm)
Sources: S&P Platts, NETL

D Though greenfield seasonal storage is currently economically challenged in Houston, a path to viability exists

Annualized margin per MWh for greenfield gas turbine using stored H2 for seasonal price arbitrage, $/MWh[1,2]

Scenario:	**Greenfield gas turbine with seasonal dispatch**	**Brownfield**	**Further Levers**
Description:	H2 produced during low power price periods, stored in existing salt caverns, and burned in gas fired turbine (506 MW) to dispatch power on the grid seasonally (240MW/h) during high price periods	Blend H2 with NG in existing gas fired power plant	Realize lower prices as renewable penetration grows or exploit lower electrolyzer costs as scale/technology improve



DOE grant awarded to GTI to further investigate options to leverage utility scale salt caverns in TX Gulf Coast area

Notes: (1) Low priced power is $13.21/MWh, (2) Reduced electrolyzer capex is $750 / kw
Sources: ERCOT, EIA, H2City Model, Gencost, Barclays, OSTI – Port Arthur Study, DOE

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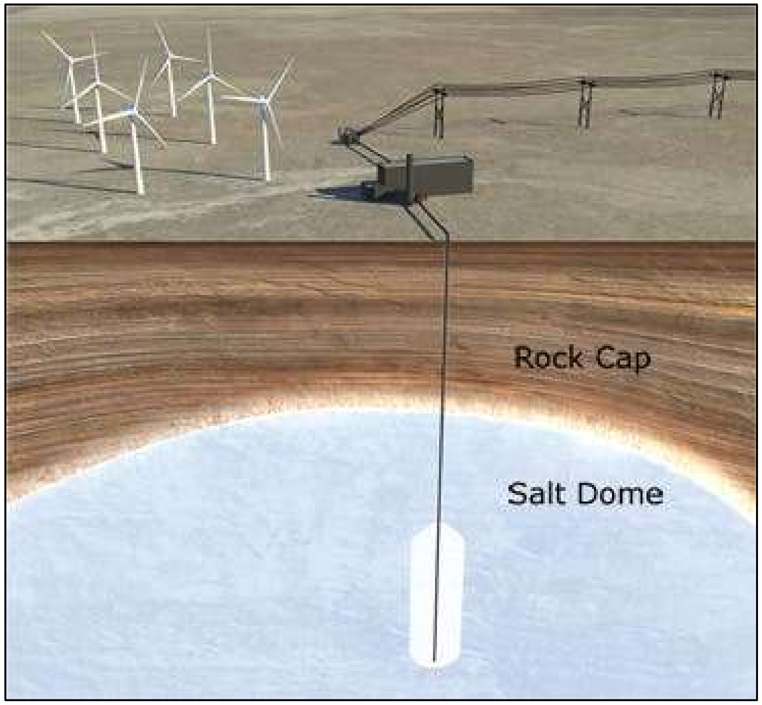
E A brownfield project in Delta, UT is underway exploiting similar economic levers

Delta, Utah H2 storage schematic



Key stakeholders

MAGNUM Development · IPA Intermountain Power Agency Energy for Today & Tomorrow · MHPS · LA DWP · Haddington Ventures, L.L.C.

Project insights

- Drive from CA and UT stakeholders for the local power agency to convert existing coal-based power to clean power
- Combination of curtailed renewable power and utility scale salt caverns provide enablers to generate and store H2, which is blended with NG to decarbonize electricity
- Leverages existing coal-plant transmission infrastructure
- H2 piggy backs off of to-be-built gas-fired power plant
- Project costs $1.9B (end to end system) funded by Magnum and Mitsubishi Hitachi Power Systems

Notes: (1) Intermountain Power Agency (IPA) provides electricity to Southern CA and other locations in UT; (2) IPA is operated by the LA Power and Water Authority; (3) Application for Department of Energy grant in near future
Source: Mitsubishi Hitachi Power Systems, Forbes, Power Technology, Los Angeles times

F Market/policy enhancements in TX could further increase the value of renewables and enhance viability of green H2

Preliminary options

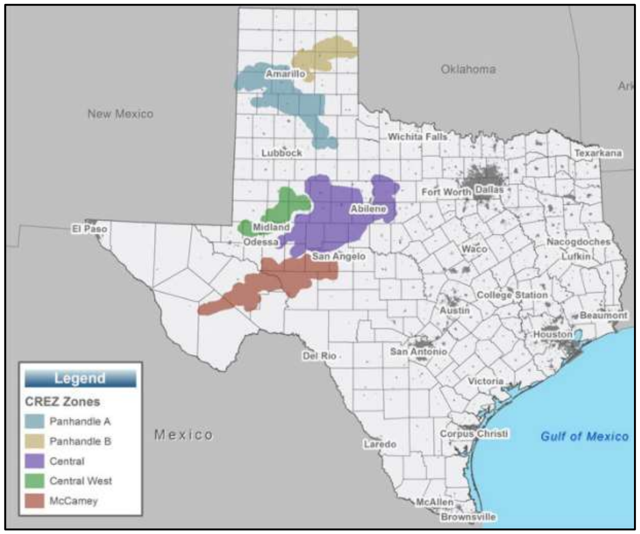
Renewable purchase requirements

- **Option:** require power retailers and municipalities to acquire minimum (and escalating) amounts of renewable power
- **Rationale:** Provides incentive for construction of additional capacity to meet acquisition mandates

Transmission & distribution

- **Option**: establish next wave of competitive renewable energy zones (CREZ)
- **Rationale:** CREZ was an effective tool for enabling wind transmission development in TX; could further maximize existing and new renewables by capturing low revenue hours

ERCOT CREZ for wind



Tax policy

Carbon tax / cap and trade

- **Option**: institute carbon tax / cap and trade system for carbon emissions
- **Rationale**: Utilized in regions to set limit on emissions, while allowing emitters to cut lowest cost emitters first; potentially increasing low carbon energy use and investment

Renewable asset tax credits

- **Option:** extend tax credits for solar and wind development
- **Rationale:** credits have driven uptake and improvements
  - Production Tax Credit for wind expires after 2020
  - Investment Tax Credit for utility solar decreases from 22% to 10% after 2021

Notes: (1) Expiration of tax credits refer to projects that start construction after the year indicated
Sources: ERCOT, energy.gov, Solar Energy Industrial Association (SEIA)

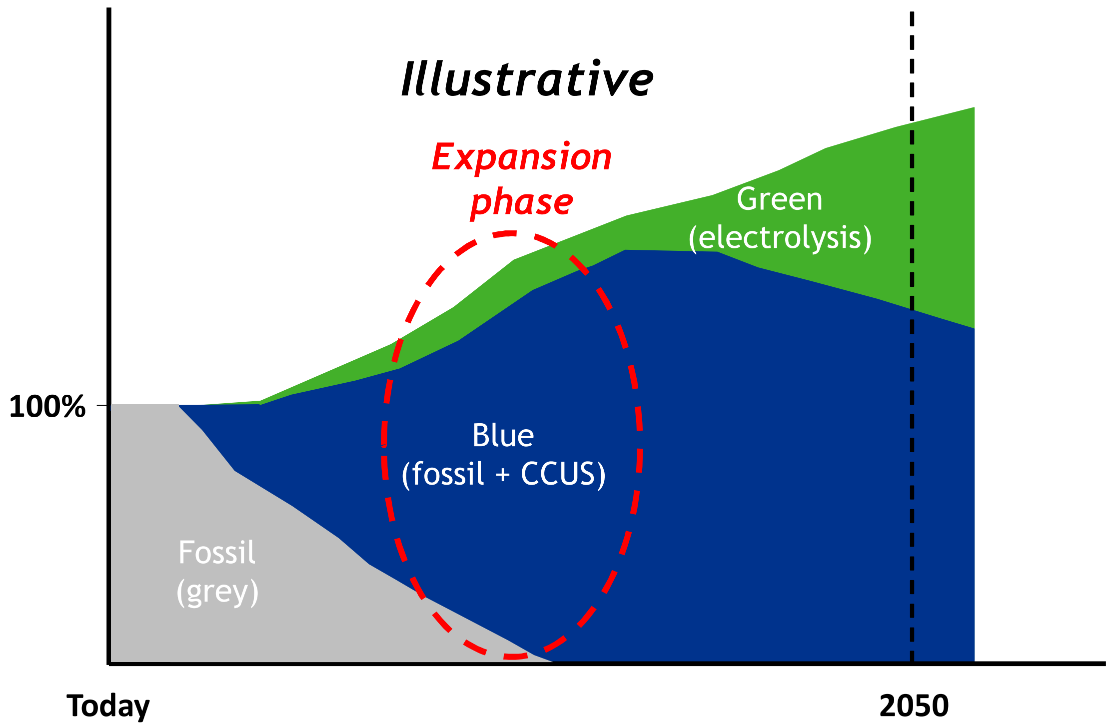
B E Several next steps are required to leverage Houston's H2 storage advantages and anticipate TX storage needs

Critical steps to advance H2	Potential next steps
TX: renewable penetration & H2 storage	▪ Assemble policy-shaping coalition to: – Evaluate funding / policy (e.g., CREZ 2.0) required to support further renewables penetration, enable maximizing renewable asset value, and ensuring reliability with increasing levels of renewable penetration
Houston: H2 seasonal storage	▪ Conduct feasibility study (potentially GTI DOE study) of options to use Houston's salt caverns for H2 storage (e.g., seasonal storage in Houston, store H2 and blend with natural gas to reduce emissions with power plants), identifying advantaged uses, emissions impacts, and barriers ▪ Assess policy needs and gaps and propose changes

Agenda

Expand phase H2 focuses on scaling up and exporting blue H2, while fostering green H2 with advantaged market(s)

Hydrogen demand and mix (illustrative)



Expand phase - blue capital

Scaling blue H2 production

- **A** Increasing global demand
- **B** Building on Houston's advantages and expanding blue production

Potential H2 exporter

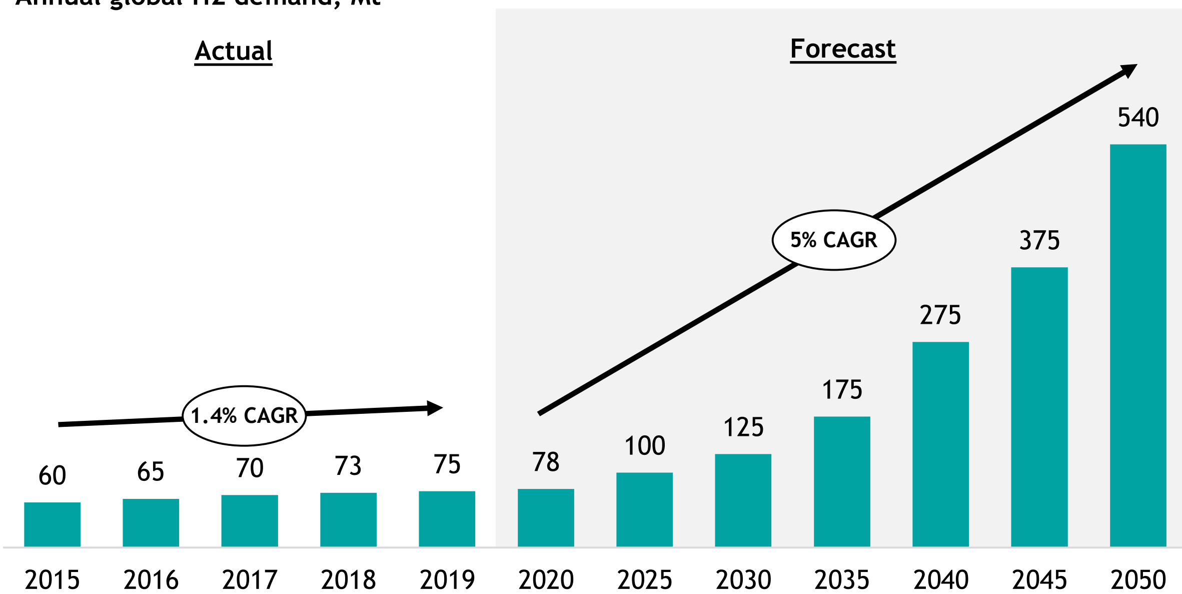
- **C** Preliminary export markets (e.g., CA for LCFS, Rotterdam)

Coupling TX green H2 advantages with improved electrolyzer economics

- **D** Projected renewables growth, electrolysis improvement, and policy may increase green role
- **E** Opportunity to further decarbonize transit - buses

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

Annual global H2 demand, Mt



By 2050:

- **$950 billion** hydrogen gas market
- **$2.5 trillion** hydrogen and support equipment market

Sample of potential markets importing H2

Net short H2 regional import hub (e.g. Rotterdam)	US states with potential shortage due to policy drivers (e.g. CA)	Early market driven adoption (e.g., heavy transportation corridors)

Source: Barclays, HSBC, Hydrogen Council

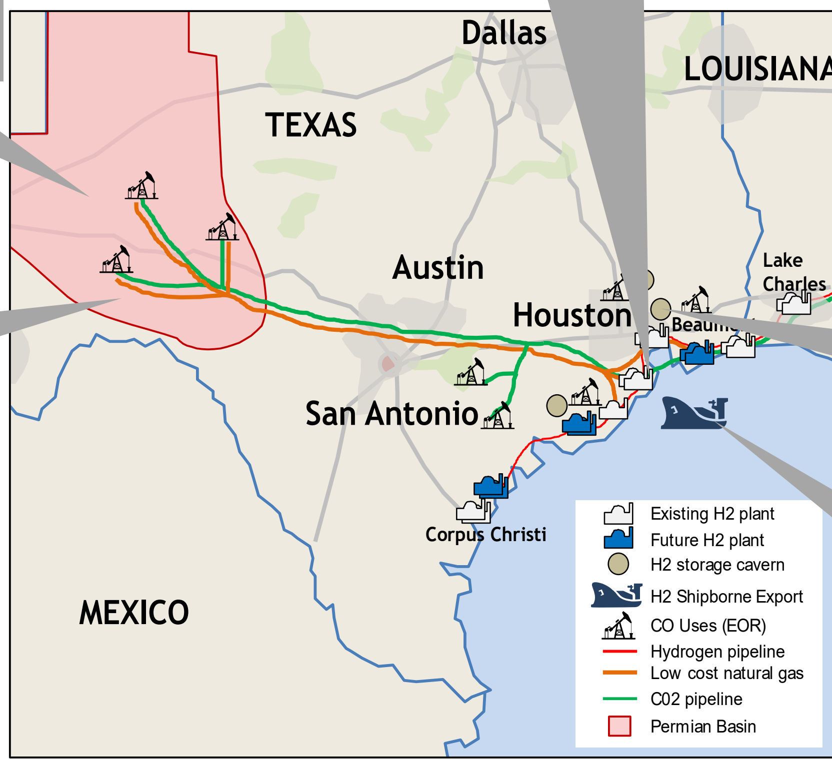
B Houston area structural H2 production and CCUS advantages suggest the potential for a scale cost export role

Case for Houston as global blue export capital

Opportunity to create low-cost, at-scale CCUS system; 95% clean H2

World scale in-place H2 production capacity

Global low cost natural gas feedstock



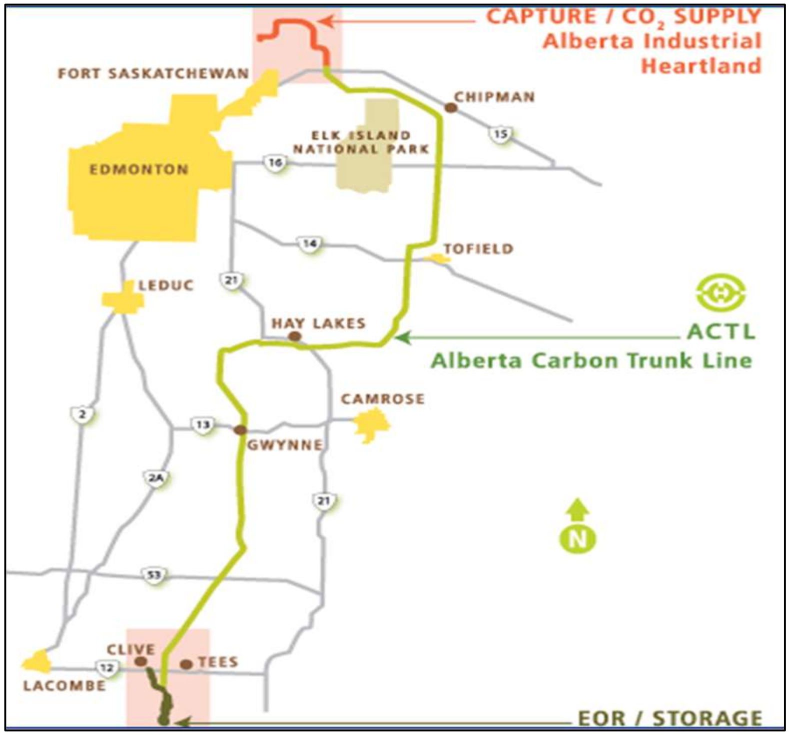
Global H2 storage and transport infrastructure leader

Leading commodity export port

B

To mitigate core business carbon risk and enable new markets, Alberta installed a scalable CCUS system

Schematic of the Alberta CO2 Trunk Line (ACTL) System



Stakeholder participation

NWR, Nutrien, Wolf Midstream, Enhance Energy Inc., SAW Engineering Private Limited

ACTL project insights

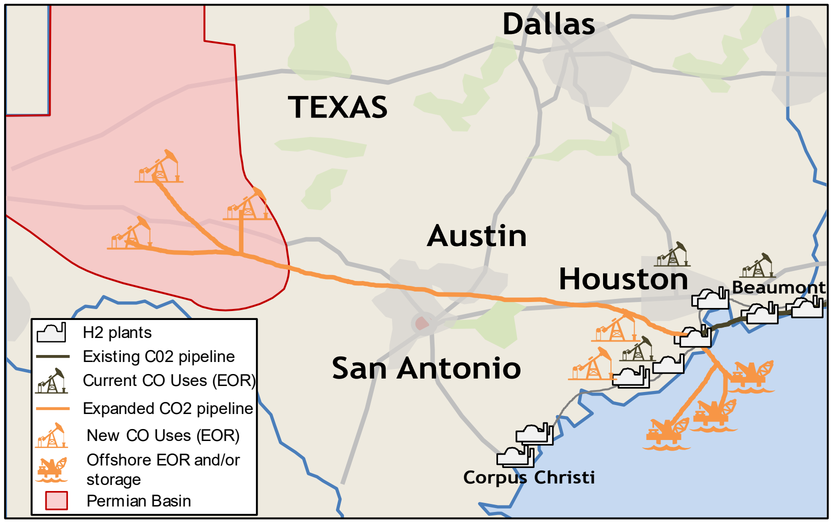
- Extensive O&G industry is historic CAN prosperity driver, **at risk without carbon mgt. system**
- Alberta government facilitated **competitive process to reduce emissions**; two CCUS projects selected (ACTL, Shell Quest)
- **ACTL captures, transports, and utilizes CO2 for EOR**
  - Initial CO2 captured totals (1.6 Mt CO/yr) from bitumen refinery and fertilizer plant
  - **Potential to scale system 10x to 14.6 Mt CO/yr**
- Funding ($1.2B) provided by Alberta government ($495M), CAN government ($63M), and remainder by Enhance Energy
- Potential to **integrate blue H2 for attractive markets** (e.g., Alberta blue H2 freight truck pilot)

Notes: (1) H2 emissions from SMR, by-product, and other based on ratio of 9, 6.8, and 3.4 kg CO2 for each kg of hydrogen produced via SMR, (2) SMR'S CO2 emissions in 2016 and other GHG emissions in 2014
Sources: US EPA Greenhouse Gas Reporting Program (GHGRP); Environmental Science & Technology; H2tools; US DOE

B Two steps are critical for Houston to become a major blue H2 exporter: expand the existing CCUS system and build new blue capacity

Step 1: *Expand existing CCUS system*

Illustrative existing and expanded TX GC CCUS system

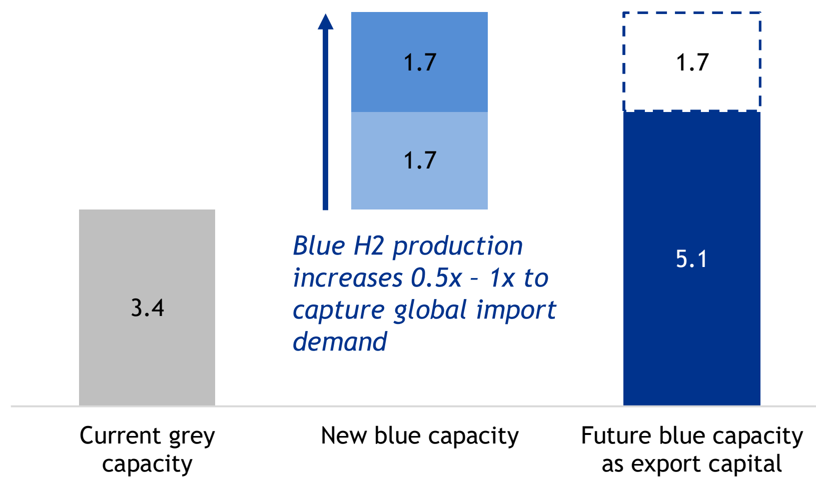


Key considerations

- **Capacity:** accommodate (1) converting remaining grey H2 to blue and (2) building new blue ATR/SMR
- **Usage / storage**: utilize for EOR (e.g., Permian) and/or storage in (1) TX Gulf Coast and (2) Extending into Permian
- **Infrastructure:** carbon capture at plants; expanded, integrated CCUS pipeline from CO2 sources to CO2 uses / storage

Step 2: *Build new blue capacity*

Indicative blue H2 production capacity as export capital, Mt H2/yr



Key considerations

- Capturing global clean H2 demand requires substantial production
- TX Gulf Coast system is 80-90% utilized based on industrial gas provider interviews, requiring new production
- Other global regions (e.g., Rotterdam, Humber UK) have utilized blue ATR to achieve low cost, production at-scale

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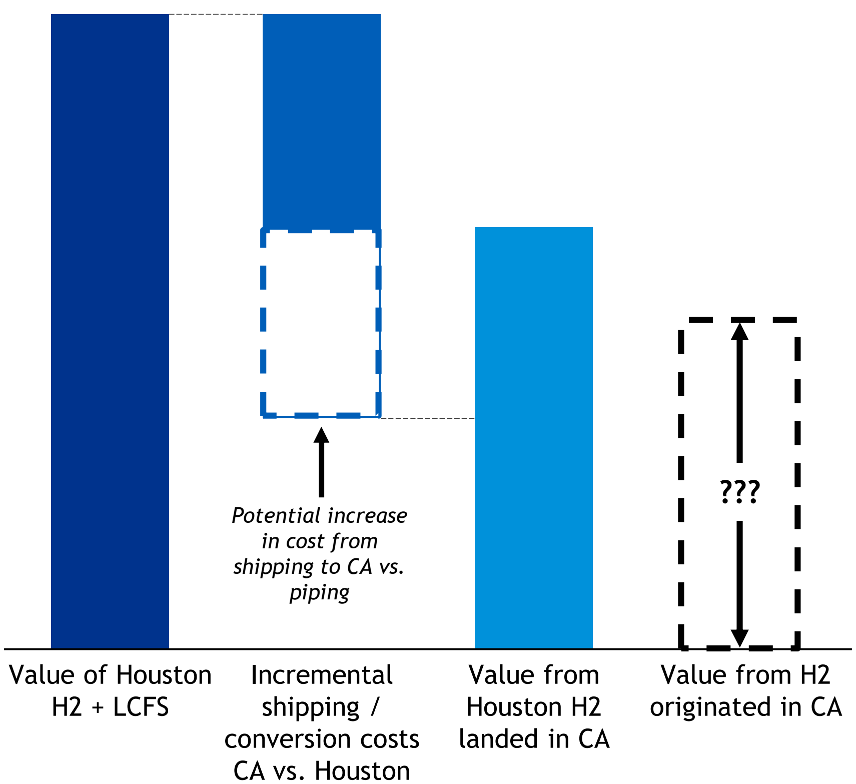
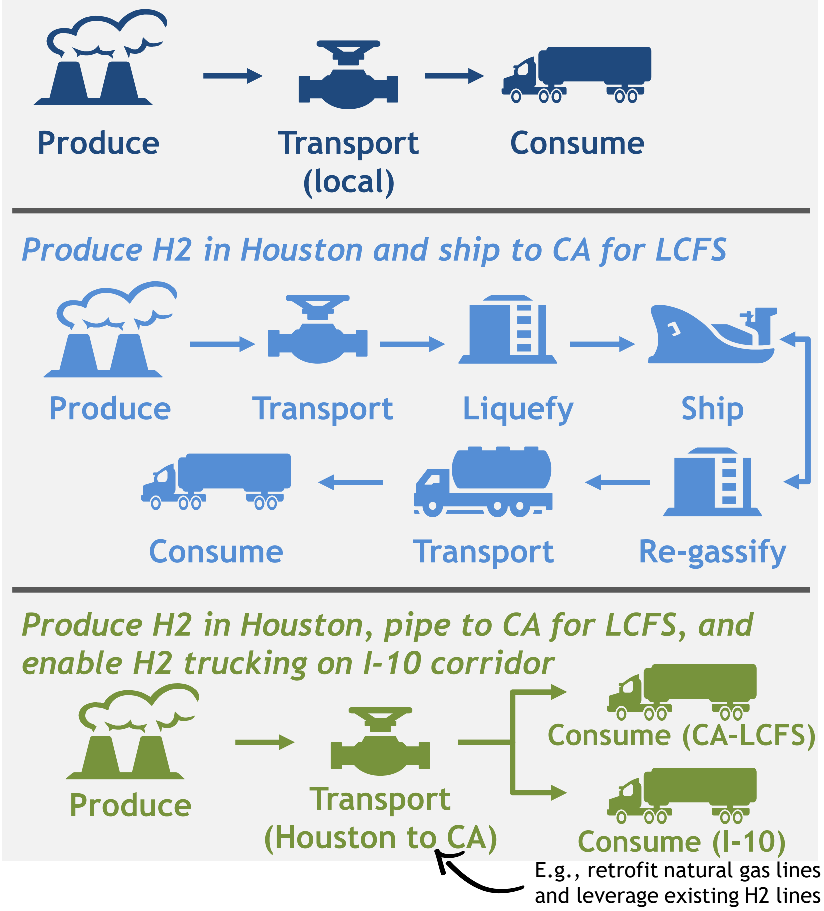
Initial markets to export blue H2 may include CA for LCFS and/or the I-10 corridor to enable trucking

Illustrative economics for selling TX produced hydrogen in CA to leverage LCFS



Value chains to sell H2 in Houston vs. export to CA



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- Blue and green market upside as trends evolve

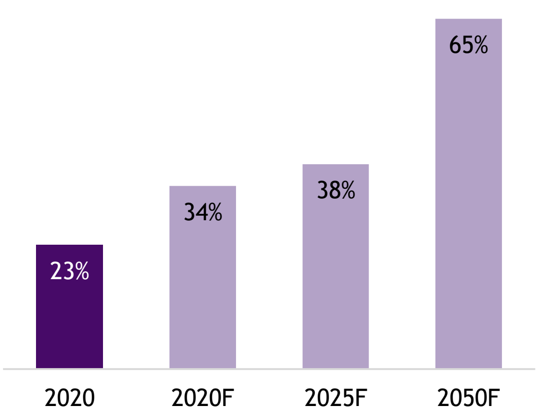
Chapter 4: Integrated Greater Houston H2 roadmap and next steps

Appendix

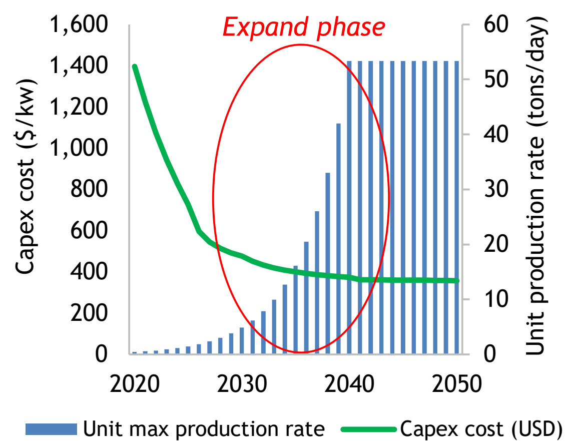
D Projected renewable penetration, electrolysis improvement, and policy trends could create an expanded role for green H2

Key green production drivers in expand phase

1 TX renewable penetration, %[1,2,3]



2 Electrolysis cost and production



3 Market enhancements and policy examples

- Renewables procurement mandates
- Renewables tax credit
- Carbon tax
- T&D policy

Implications

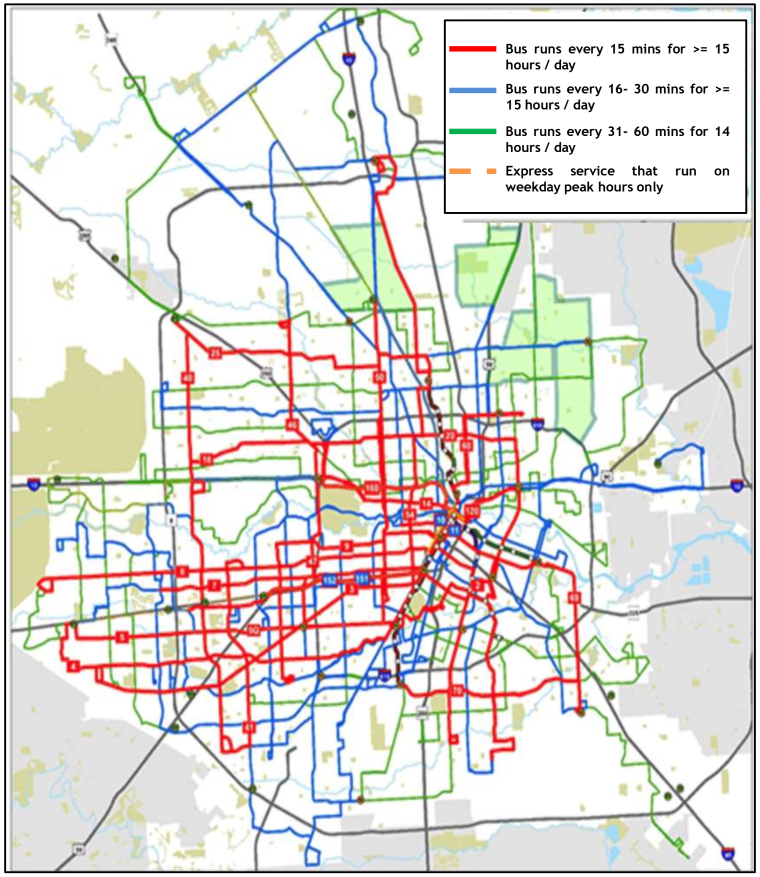
1. Growing renewable penetration increases need for long duration storage and reduces power prices
2. Manufacturing at scale will drive cost efficiencies and technology advancements
3. Momentum of market and carbon policy are unknown in US and TX

Notes: (1) 2025F assumes pipeline installed by 2025; (2) 2025F penetration assumes linear penetration given capacity/penetration levels from 2022 and 2022F; (3) 2050F represents NREL 2050 base case for TX VRE penetration
Source: Cleantech Group, Rocky Mountain Breakthrough Batteries, Apex Compressed Air Energy Storage, ERCOT, NREL, Lawrence Berkley National Lab, CSIRO

For example, expanded green hydrogen could play a role in progressing heavy transportation decarbonization by fueling transit buses

E

Houston metro bus routes



Houston metro bus segments: overview and pro's/con's of H2 entry

Potential advantage for H2

Transit: extended cycle

Daily bus count[1]: 200
Duty cycle: Extended operations (20hrs/day)
Pro's for entering with H2
- Lower emissions than diesel
- Provides extended range vs. BEV buses

Con's for entering with H2:
- Overcoming new infrastructure and lack of operational experience

Transit: standard cycle

Daily bus count[2]: 580
Duty cycle: standard operations (12hrs/day)
Pro's for entering with H2
- Lower emissions vs. diesel

Con's for entering with H2
- Shorter routes may be more suitable to decarbonize with BEVs

Park and ride

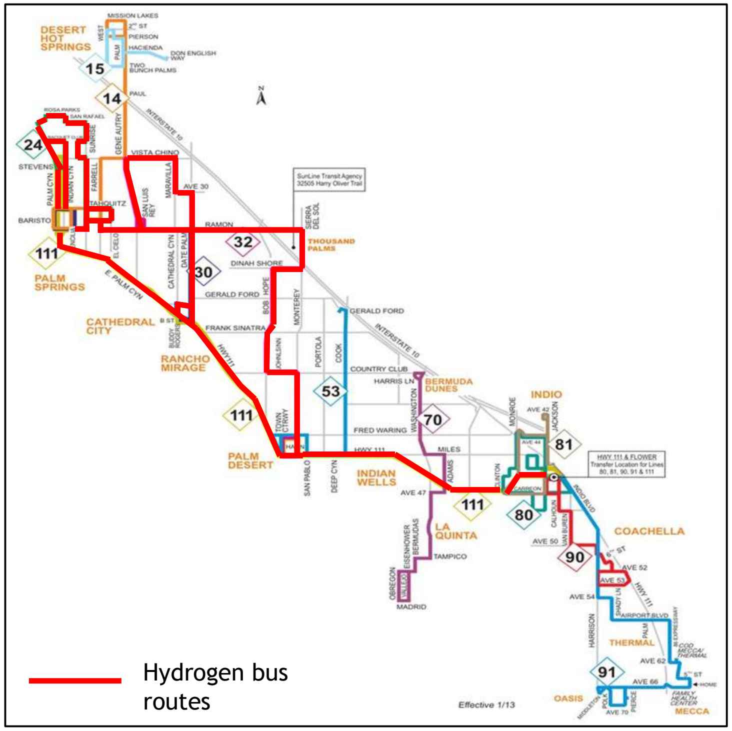
Daily bus count: 462
Duty cycle: TBD
Pro's for entering with H2
- Lower emissions vs. diesel

Con's for entering with H2
- Shorter routes may be more suitable to decarbonize with BEVs

Notes: (1) Number of buses for T.E cycle is 25% of total 780. (2) Number of buses for T.S cycle is 75% of total 780
Source: Houston metro

E The SunLine transit agency in CA, for instance, has transitioned from diesel to CNG to H2 buses

SunLine Transit Agency Bus Routes



Key stakeholders

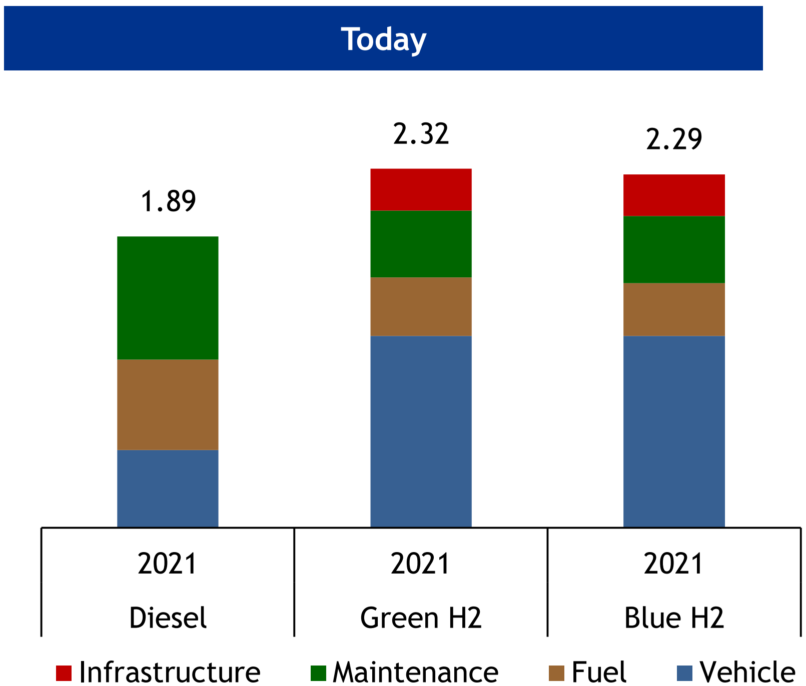
Project insights

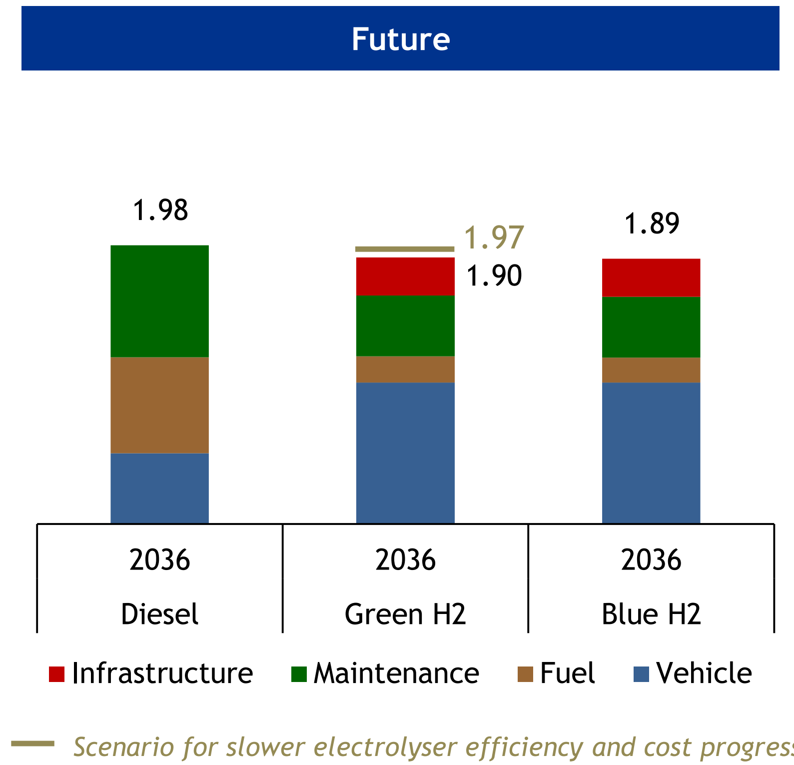
- H2 bus pilots initiated following the Innovated Clean Transit regulation (2018) that requires public transit agencies to be zero emission by 2040
- Three pilots (15 buses, 1 station) have progressed to test the feasibility of routes that operate 20 hours / day
- Pilots funded by US government and CA Climate Investments ($23.8M)
- Pilots were successful, and Sunline plans to shift its CNG fleet to zero emission buses (currently 15 FCEVs and 4 BEVs)
- Fuel for the pilots was a mix of green and blue H2, and the agency has installed an electrolyzer to provide green H2 for future buses

Source: NREL SunLine Transit Agency, California Air Resources Board, H2 View, U.S. Department of Energy

E Preliminary analysis shows H2 competitive with diesel in extended run duty, over time

Total Cost of Ownership for diesel vs green (brown power) hydrogen buses ($M/bus)[1,2,3,4]





Notes: (1) Miles driven per 310/day/bus, 360 days/year; (2) pilot, expand and rollout phases each run 10 years; (3) Base and slower case assume electrolyzer case assumes electrolyzer efficiency and capex cost / unit decrease 79% by 2050 per CSIRO; (4) Base case assumes exponential decrease to CSIRO target, slower case assumes linear decrease

Source: H2city tool, NREL, FSH JU

Several next steps are required to expand H2 market penetration both locally and for export

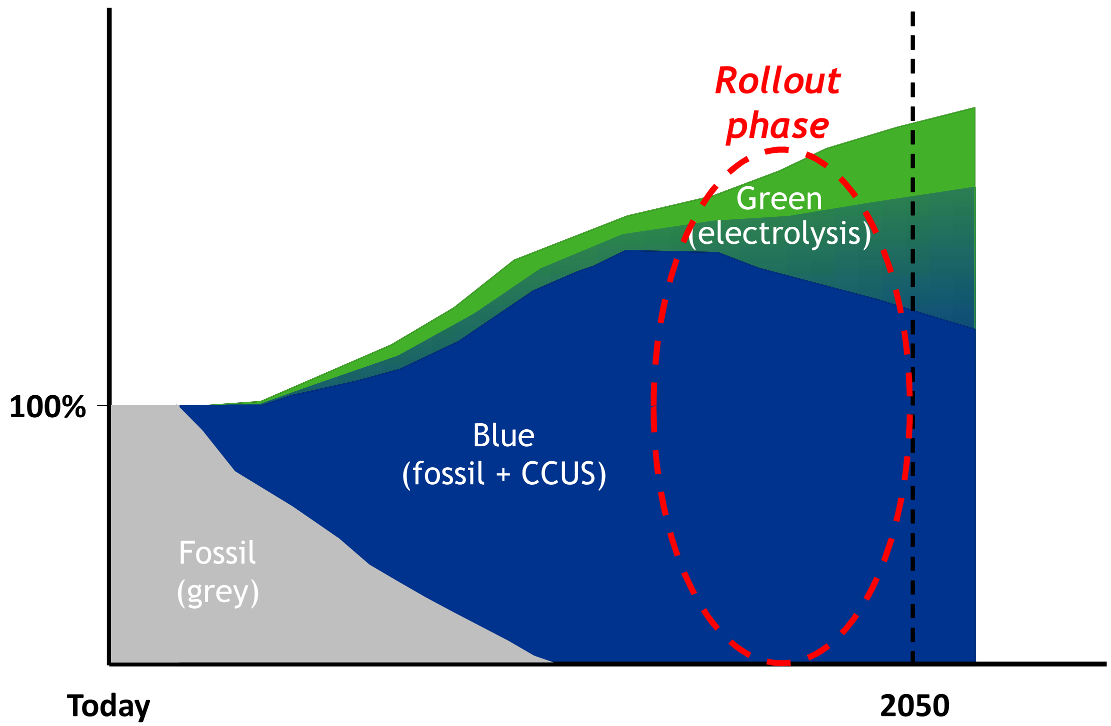
C E

Critical steps to advance H2	Potential next steps
CCUS expansion	▪ Convene coalition across CCUS value chain, such as industrial gas providers, midstream/ CCUS providers, EOR/E&P and other CO2 users, existing industrial CO2 emitters ▪ Confirm prioritization of utilizing existing Denbury CCUS system to support converting grey to blue, develop roadmap for additional phases and extending blue H2 production ▪ Conduct detailed planning and costing for 'Activate' phase ▪ Determine funding and policy support required
Blue export markets	▪ Bring together stakeholder coalition across H2 export value chain, such as industrial gas providers, pipeline operators, and energy co's and shippers with low carbon commitments ▪ Conduct scoping economics of export opportunity to CA for LCFS (i.e., leverage pipeline right-of-ways to retrofit/greenfield vs. waterborne shipping) ▪ Explore potential Houston to CA H2 pipeline for synergies between I-10 heavy trucking and export to CA for LCFS
H2 transit buses	▪ Assemble stakeholder group across the transit bus chain, such as Houston METRO, industrial gas providers, bus manufacturer, and station developer/operators ▪ Evaluate and optimize economics for pilot study of H2 buses on extended routes in Houston METRO ▪ Identify required and available funding to support pilot study, and potential policy support approaches

Agenda

The rollout phase for H2 in Houston is uncertain and depends heavily on a variety of forces…

Hydrogen penetration and mix (illustrative)



"There is no guaranteed pathway as to how demand and supply for hydrogen will develop, given uncertainty over cost and policy developments…"
- Barcylays

Rollout phase - H2 economy

Long term forces at play, and potential investment required to enter and scale blue and green H2

- **A** Forces impact the extent and pace of utilizing clean H2
- **B** Potential improvements needed to achieve blue and green at-scale

H2's potential role in decarbonizing Houston's industrial processes

- **C** Significant emissions from Houston's industrial processes
- **D** Analog projects / regions use of blue H2 to decarbonize their industrial processes
- **E** Transformation required for blue and green to achieve cost and scale needed for industrial processes

Ⓐ Multiple forces will significantly shape demand, pace, and source of H2 in decarbonization over the long run

Interrelated Forces that will Shape the Houston H2 Economy

Public carbon policy and funding

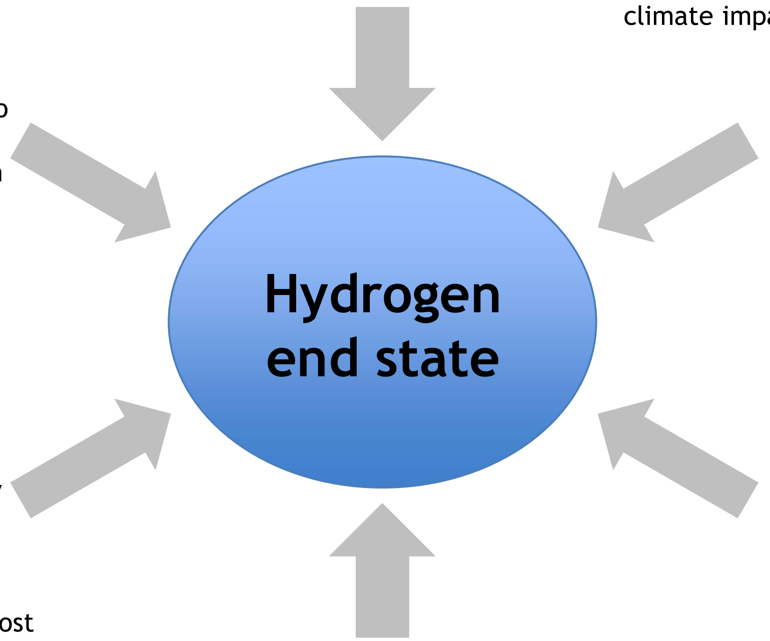
- Extent of federal and state carbon reduction incentives and taxes
- Public policy postures toward climate impact

CCUS technology, economic, and uptake trends

- Technology advancements to reduce cost burden (e.g., direct air extraction, carbon fibers)
- Pacing for emitters to adopt CCUS, multiplier effect for production scale economies

Decarbonization goals and timing

- Country/region/state/company net-zero goals
- Pace to achieve net-zero goals



Renewable and electrolysis technology and economic trends

- Technology advancements to increase efficiencies, reduce cost burden
- Rate of power cost declines
- Extent of renewables on grid, further driving benefits of H2 storage

Consumer / corporate perspectives

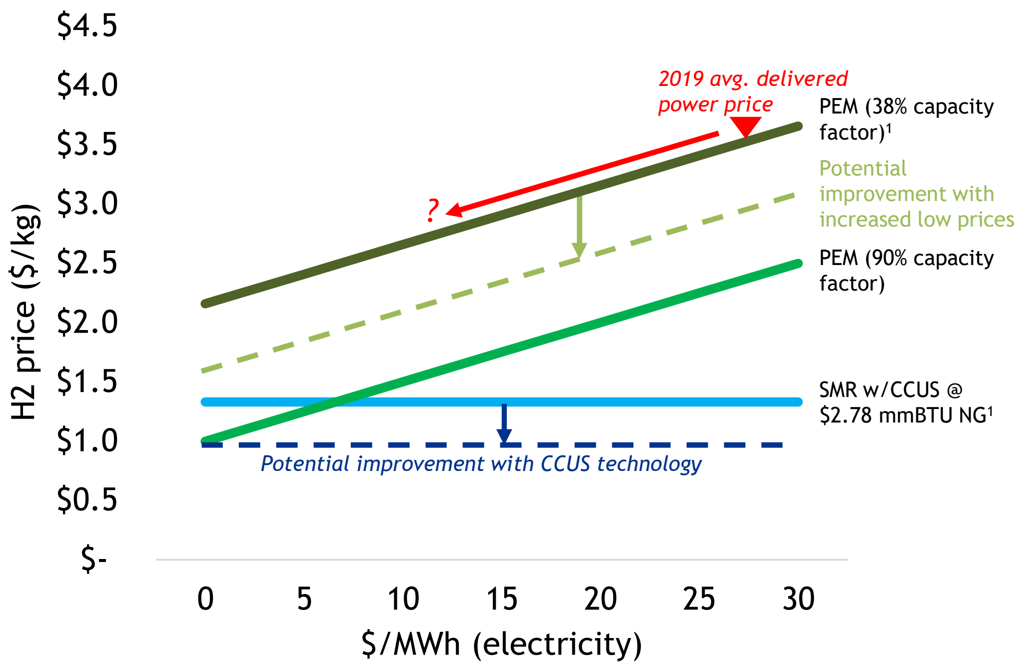
- Consumer buying behaviors toward low carbon products and companies
- Employee sentiment toward carbon commitments

Investor preferences and impact investing

- Investor pressure/shift to low carbon companies
- Investment rates in low carbon technologies, accelerating innovation

Cost and technology advances expected for blue and green, though greater gains required for green to be competitive

Current Houston blue and green H2 production costs



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

Potential improvements for blue

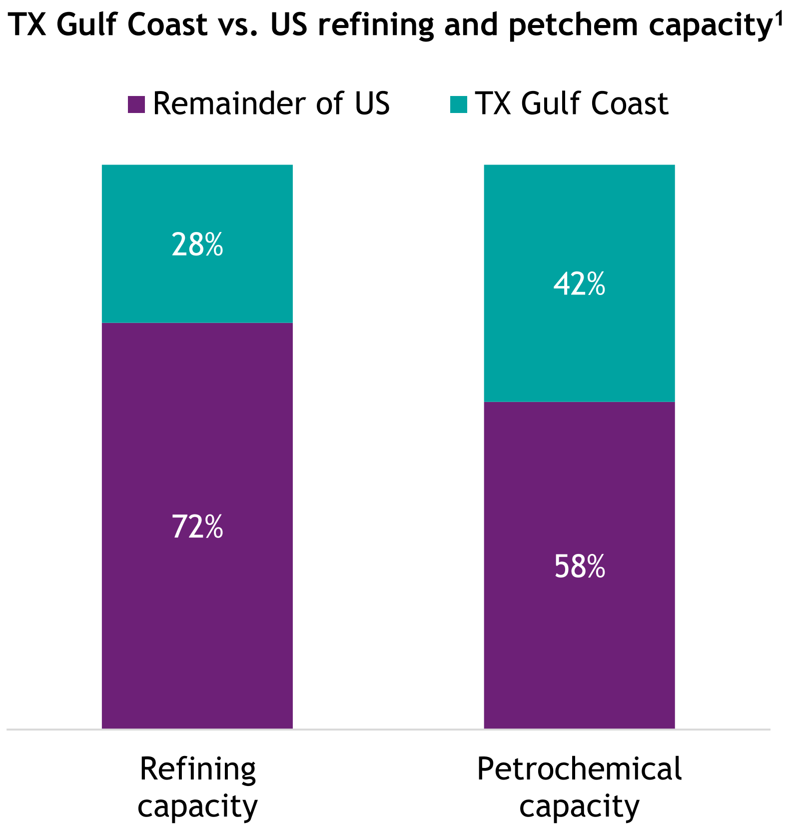
- Continued improvements in CCUS cost and technology
- Policy instituted to support CCUS adoption
- Retaining low methane cost

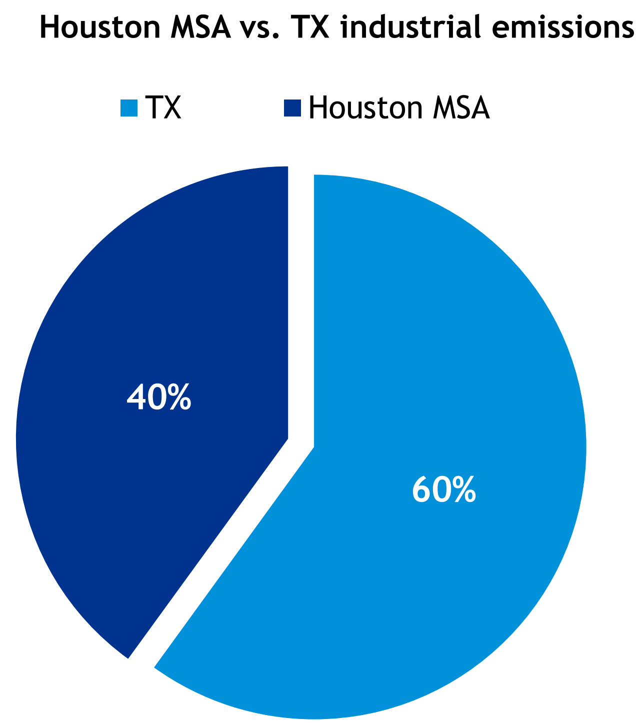
Potential improvements for green

- Electrolyzer cost and technology materially improve
- Substantial renewables penetration drives ubiquitous low price power
- Policy and investor sentiment favor green H2

Notes: (1) Capacity factor of 38% represents extent of 2019 "low price" hours in Houston
Sources: S&P Platts

H2 could play a unique role in reducing emissions resulting from Houston's vast industrial processes

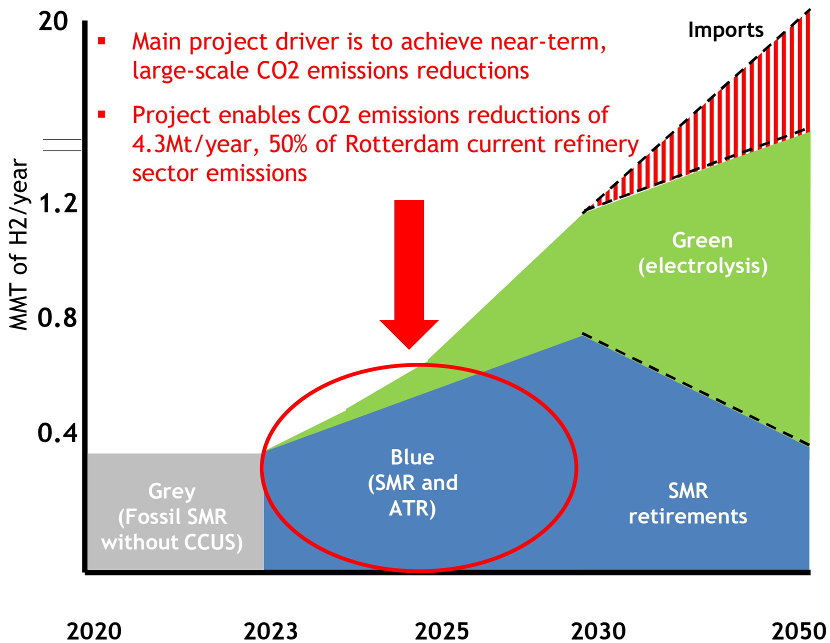




Notes: (1) Texas Gulf Coast refers to Houston area
Source: EIA, Barclays Research

D For example, Rotterdam is leveraging blue H2 at scale and policy enablers to decarbonize its industrial processes

Rotterdam hydrogen production mix (illustrative)



Decarbonization methodology screening

Option to decarbonize	Industrial Processes: Refinery fuel gas	Industrial Processes: Other high temp	Industrial Processes: Power	Emission Reduction Efficiency[1]	Scalability[2]
Blue ATR H2	Viable	Viable	Viable	High	High
Green H2	Not viable	Viable	Viable	Low	Low
Biomass	Not viable	Viable	Viable	Medium	Low
Green power to heat	Not viable	Partially viable	Partially viable	Medium	Low
Post combustion CCS	Viable	Viable	Viable	High	Medium

Viable

Partially viable

Not viable

Infrastructure investment and pathway for long-term green H2

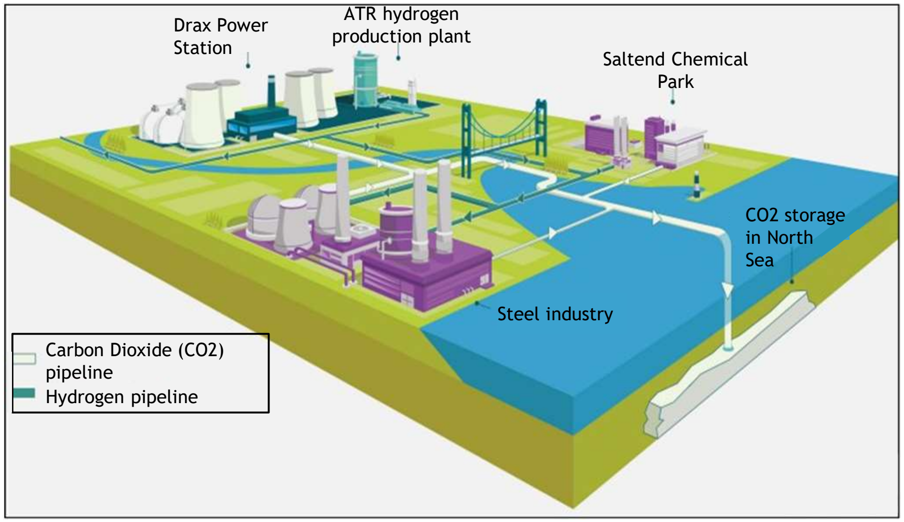
- **Industrial power:** modify gas power plants to partially utilize H2, and revamp coal plants to use biomass and H2 as feedstock in lieu of coal
- **Industrial process heat:** install new burners and supply systems to fire H2 instead of natural gas, refinery fuel gases, and naphtha gas
- Infrastructure adjustments for H2 today are not bias towards blue H2 and can be leveraged to support future scaled green H2
- Install CCS infrastructure systems at plants and tie-ins to CO2 pipeline system; permanent CO2 storage provided by Porthos project

Notes: (1) Emission reductions efficiency refers to the relative avoidance costs (€ t/CO2) among the decarbonization options; (2) Scalability refers to the relative ability to decarbonize industrial processes at scale
Source: H-Vision Final Report

Similarly, Humber, UK leverages blue H_2 at scale and policy enablers to decarbonize industrial processes

D

Schematic of Humber, UK Industrial Area



H2H project insights

- Project supports UK's aim to establish a low CO_2 industrial cluster by 2030
- Provides mechanism to reduce current CO_2 taxes incurred by area operators
- H_2 utilized by building new ATR plants with CCUS
- Initially, 900k tons CO_2/year reduced by replacing fossil fuels with H_2 in industrial processes and power
- Specifics for costs / funding not announced (FID planned for 2023)
- Potential for government funding via the Industrial Strategy Challenge Fund (government fund established to address industrial challenges)

Key stakeholders

equinor ZEROCARBON HUMBER INDUSTRIAL STRATEGY drax

Source: Equinor, Power Technology, Renewables Now, Financial Post

E

Advancements across several enablers may open the pathway for blue H2 in decarbonizing Houston's industrial processes

Required enablers to decarbonize industrial processes with blue H2

Blue H2 production at scale

- H2 is required at scale to provide energy levels necessary to supplant natural gas or off-gas currently used in industrial processes
- Advanced blue H2 manufacturing technology (e.g., Auto Thermal Reforming)can enhance CO2 capturability and operating flexibility

CCUS at scale

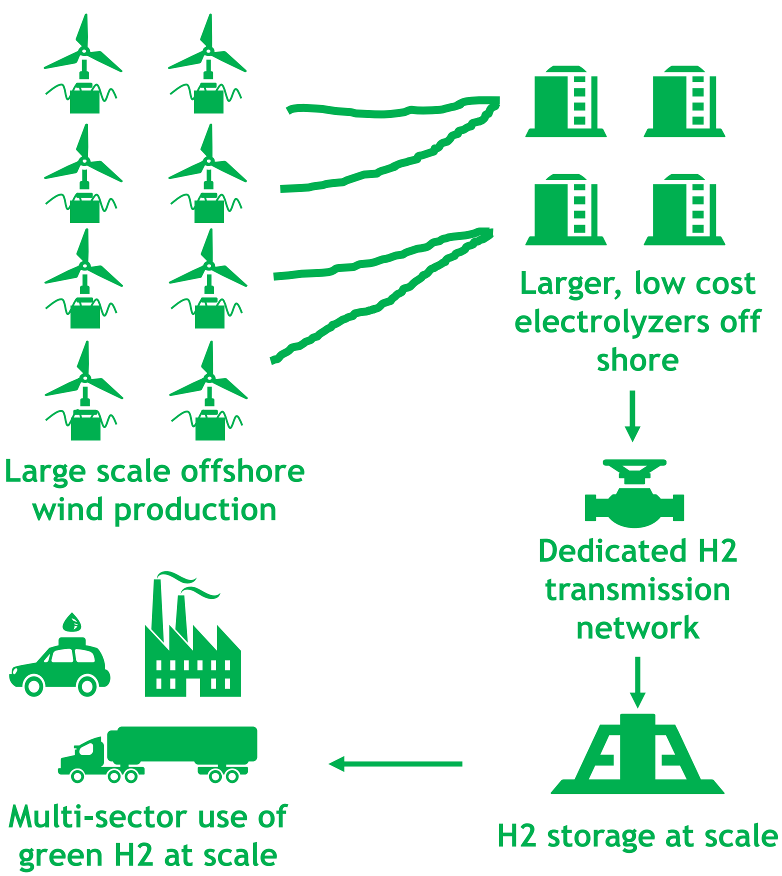
- Substantial uptick in blue H2 production will drive up level of CO2 capture needs, creating corresponding need for increased integrated CCUS system scale

Policy/cost reductions

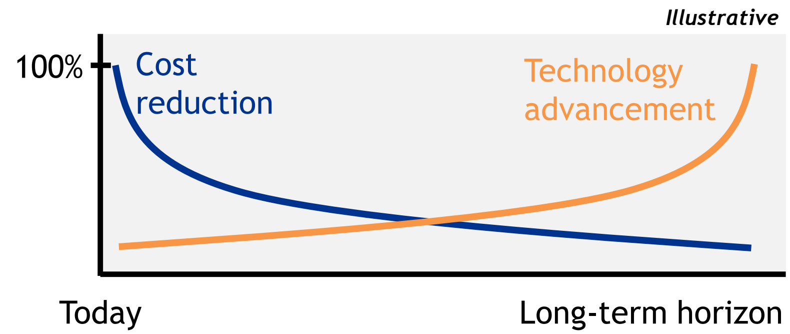
- Significant retrofit / rebuild costs are required to decarbonize industrial processes
- Other countries have employed a carbon tax to incentivize decarbonization in the industrial sector

E Green H2 may also be an option, as technology/cost advancements lead to ubiquitous low cost renewable power and low cost electrolysis

Conceptual chain for green H2



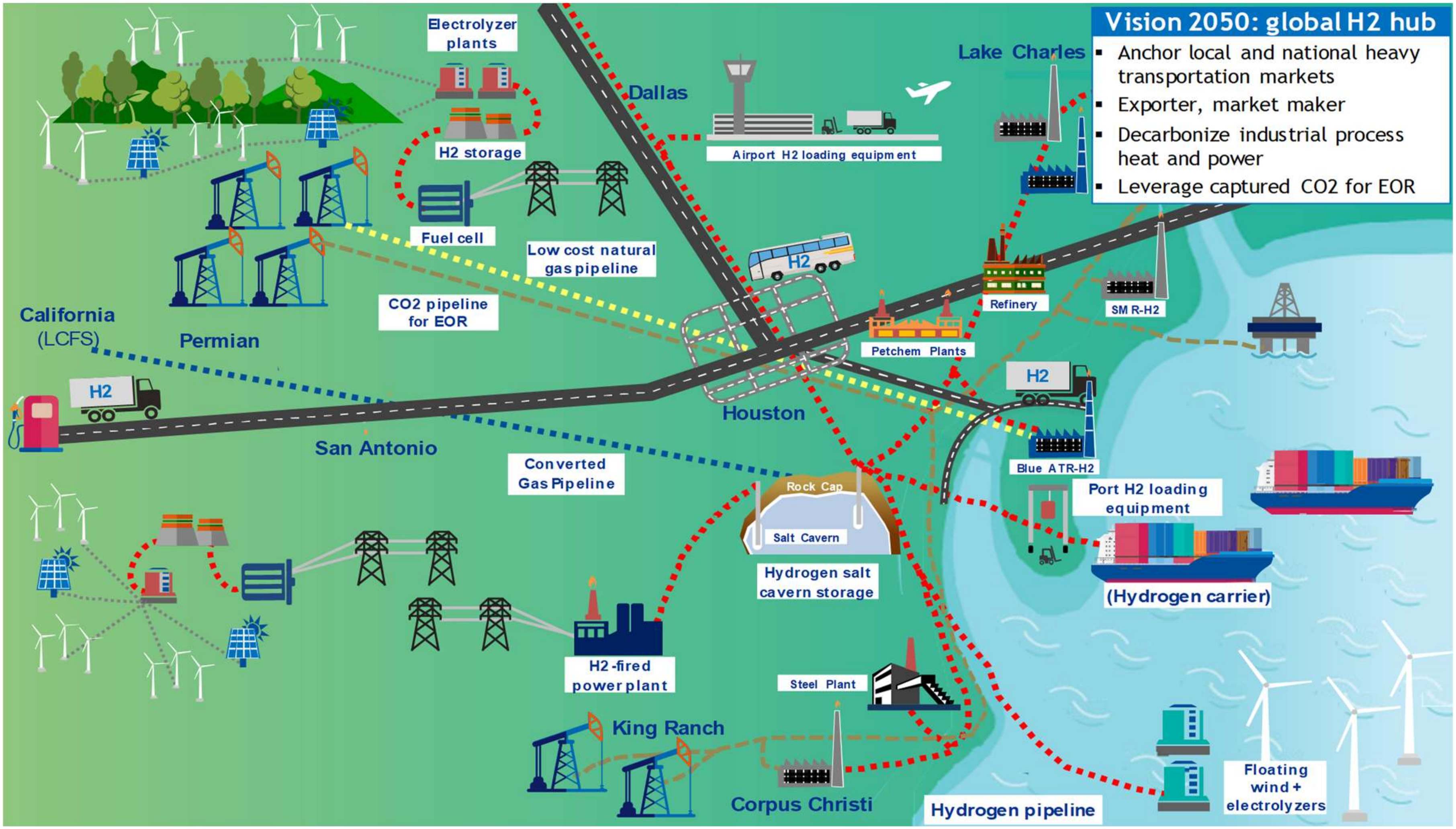
Several technology and cost advancements are required:



- Large scale floating wind production
- Offshore, low cost electrolysis
- Salt-water electrolysis
- Long range offshore to shore H2 transmission
- Scale onshore H2 storage and conversion infrastructure

Agenda

Potential Houston '2050 vision': local, national, and global flywheel for H2 penetration into heavy industrial markets



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Several phases of action over time are required to reach the potential of becoming a global hydrogen hub

Houston Hydrogen Roadmap

	Activate 2020 - 2030	Expand 2030 - 2040	Rollout 2040 - 2050?
Guiding principles	*Focus on leveraging existing assets and incremental economics to use H2 in most advantaged markets*	*Capture rapidly growing global H2 demand as export hub; scale green chains in WTX and leveraging Houston advantages*	*Position Houston to leverage advancements in technology and policy changes for clean H2*
Production	▪ **Blue**: convert grey to blue system; incremental use of existing system ▪ **Green**: build pilot electrolyzer project for seasonal H2 storage; pursue WTX long duration pilots	▪ **Blue**: expand production (~1x) to become global blue export capital ▪ **Green**: extend electrolyzer production for H2 transit buses; extend synergistically with renewables	▪ **Blue**: increase production to supply industrial processes ▪ **Green**: adopt/'drop in' new chains (e.g., large scale offshore wind and electrolyzer, H2 to shore)
Markets	▪ Industrial feedstock (clean): refining and petchem ▪ Heavy trucking in long-haul corridors and/or regional chemical ▪ Seasonal storage for price arbitrage	▪ Export to advantaged markets (e.g., CA for LCFS) ▪ Long duration storage paired with substantial and growing renewables ▪ Extended operational routes for Houston METRO transit buses	▪ Transform industrial process heat for petchem, refining, steel, and cement ▪ Utilize H2 for industrial power generation
Infrastructure	▪ Add CCUS to priority H2 plants ▪ Build H2 filling stations to enable heavy trucking ▪ Install pilot electrolyzer system for seasonal H2 storage; WTX storage	▪ Add CCUS to remaining H2 plants ▪ Extend CCUS for new CO and to enable EOR for O&G fields ▪ Construct new blue H2 plants and extend H2 pipeline network ▪ Build H2 export system ▪ Build electrolyzer capacity and H2 filling station for transit buses	▪ Expand export terminals for ammonia and/or liquid hydrogen ▪ Construct large scale offshore wind and electrolyzer systems

Each phase will require investment (and policy support)

Screening level investment summary ($M)[1,2,3]

H2 source	Market	Activate (2020-2030)		Expand (2030-2040)		Rollout (2040-2050?)	
		Investment	Cost	Investment	Cost	Investment	Cost
Blue	Heavy trucking (I-45)	▪ Pilot for freight traffic between Houston and Dallas ▪ Extend pilot to enable cumulative 2.5% of traffic	16 37	▪ Continue expansion ▪ Expand freight trucks to cumulative enablement of 25% trucks	27 197	▪ Continue rollout of freight trucks	143
	Heavy trucking (I-10)	▪ Pilot for freight traffic on San-Antonio-Houston corridor ▪ Extend pilot to enable cumulative 4% of traffic	15 15	▪ Continue expansion ▪ Expand freight trucks to cumulative enablement of 25% trucks	11 54	▪ Continue rollout of freight trucks	37
	Grey to blue (CCUS)	▪ Add carbon capture to priority H2 plants (8) and tie-into Denbury	310	▪ Add CCUS to remaining H2 plants (40), and expand CO pipeline to accommodate new CO	713		
	Blue export			▪ Build and operate new H2 plants ▪ Build H2 pipeline to export H2 to CA for LCFS and enable I-10 trucks ▪ Expand CO2 pipeline for new CO2	TBD 520 137	▪ Further extension of CO2 pipeline to West Texas	TBD
Blue / green *(H2 source TBD)*	Houston METRO buses			▪ Initiate pilot for extended operations buses ▪ Expand pilot to enable cumulative 15% of extended route buses	16 12	▪ Continue rollout of buses on extended routes	13
	Industrial processes/ power					▪ Utilize low cost H2 to decarbonize industrial processes and power	TBD
Green	Seasonal storage/ long duration storage	▪ Seasonal pilot (electrolyzer + cavern H2 storage) ▪ Conduct long duration storage pilot synergizing with renewables growth	172			▪ Expand seasonal and long-duration storage to take on integral storage and power generation role	TBD
	Renewables +electrolyzers			▪ Expand on-shore renewables, synergized with storage	TBD	▪ Potentially construct large-scale offshore electrolyzer and wind	TBD

Notes: (1) Figures shown in 2020 dollars; (2) Phase costs begin at start of initial year and end prior to start of last year; (3) Costs are discounted at 10% WACC; except CCUS (4) CCUS costs equity financed, 12% cost of equity
Sources: H2City Model, EIA, DOE Port Arthur SMR Study, ANL: HDRSAM Model, Gencost

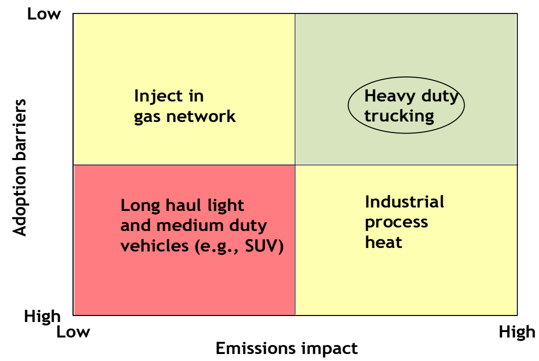
Activating the plan to achieve global H2 leadership centers on four immediate initiatives, with targeted policy/funding

Activate

Launch heavy trucking

- Leveraging existing coalitions, assemble group(s) and select / optimize the most attractive market(s) to enter
- Develop roadmap from activate through rollout

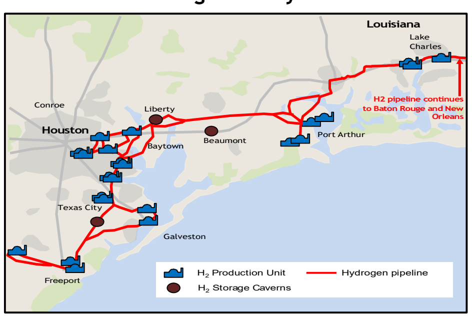
Prioritization of blue markets



Clean grey system

- Assemble coalition
- Develop a prioritized phased plan to couple the high-volume existing H2 system with existing and extended CCUS systems

Existing TX H2 system

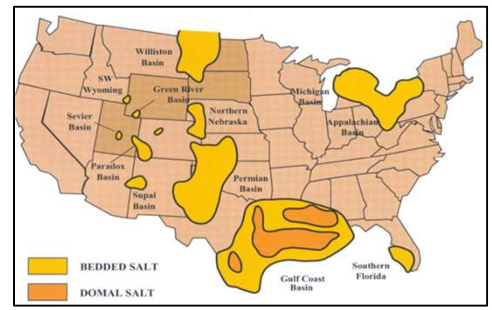


Activate

Exploit seasonal storage

- Conduct feasibility study (e.g., GTI DOE study) of most cost effective options to leverage Houston's utility scale, low-cost salt caverns for H2 storage

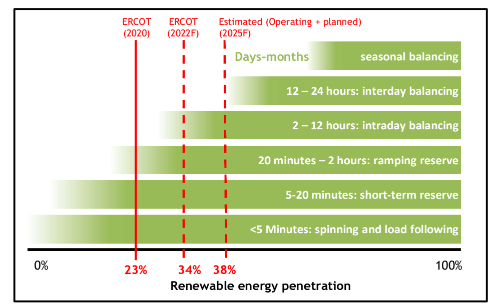
US salt cavern storage



Pilot long duration H2 storage

- PUC to assess H2 storage fit with substantial and growing renewables
- Evaluate funding/policy required to enable maximizing renewable value and ensuring reliability

Storage required by renewable penetration



Policy and funding

- Assemble group (e.g., state and federal attorneys, policy makers) to shape potential policy support for TX clean H2 economy
- Develop targeted policy / funding approach, which unleashes new attractive market opportunities, near and longer term
  - Critical to establish market opportunity for H2 and address looming impact of low carbon future on TX economy

Notes: (1) PUC refers to Public Utility Commission

Acknowledgements

Special thanks:

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Thank You!

Agenda

Appendix

- Glossary
- Key H2 market analyses assumptions (trucking, buses, storage)

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Glossary

Term	Description
Grey hydrogen	Hydrogen produced with natural gas feedstock via either the SMR process or as a by-product
Blue hydrogen	Grey hydrogen coupled with carbon capture technology to reduce the CO2 emissions (to varying degrees) during H2 production
Green hydrogen	Hydrogen primarily produced by coupling renewable electricity with electrolysis
Carbon capture usage and storage (CCUS)	An integrated series of technologies to capture carbon at sources (e.g., H2 production plants), transport the captured CO2 for potential usage (e.g., CO2 for EOR) or storage (e.g., sequestration in depleted oil reservoirs)
Heavy trucking	Truck duty cycles used to carry freight in long-haul or port drayage applications
Steam methane reformation	Process utilized to produce hydrogen by combining high pressure steam with methane to produce hydrogen
Electrolysis	Process utilized to produce hydrogen by using electricity to split water into hydrogen and oxygen
Seasonal storage	Process of generating and storing hydrogen during low price periods (either seasonally or year-round) and utilizing the stored hydrogen to produce electricity and dispatch onto the grid during seasonal high price periods (e.g., high price summer and fall)
Long duration storage	Process of storing energy (e.g., hydrogen, battery) for a period of one day or longer and subsequently converting the stored energy into electricity

Key assumptions:
TCO analysis for H2 vs. diesel trucks on I-45, Houston-Dallas corridor

Specification	Activate (2021)	Expand (2026)	Rollout (2036)
General			
Duty cycle		Long haul	
Route / area		Round trip from Houston to Dallas (I-45)	
Annual miles travelled per truck[1]		115,620	
Cumulative percent of trucks converted	n/a	2.50%	25%
Hydrogen			
Incremental H2 trucks converted	10	111	1,084
Number of filling stations (utilization)	2 stations total	3 (30%)	14 (37.5%)
Station dispenser count	1	2	2
Fueling rate per dispenser (kg/min)		3.6	
H2 filling station capital cost	$3,350,116	$6,980,182	$6,683,699
H2 filling station operational cost ($/kg)	$2.54	$0.53	$0.34
Onboard hydrogen storage (kg)		60	
Fuel efficiency – hydrogen (mi/kg)		9.4	
Hydrogen from natural gas ($/kg)	$ 1.16	$ 1.04	$ 0.88
Hydrogen truck capital cost ($)	$ 310,247	$ 247,444	$ 219,115
Hydrogen truck maintenance cost ($/mi)		$ 0.21	
Diesel			
Fuel efficiency - diesel (mi/gal)		5.29	
Diesel price ($/gallon)	$ 2.81	$ 2.85	$ 3.21
Diesel maintenance cost ($/mi)		$ 0.20	
Diesel truck capital cost ($)		$242,898	

Notes: (1) Miles driven per day per truck - 492, number of days driven per year – 235
Source: ANL: HDSRAM

Key assumptions:
TCO analysis for H2 vs. diesel trucks on I-10, San Antonio-Houston corridor

Specification	Activate (2021)	Expand (2026)	Rollout (2036)
General			
Duty cycle	Long haul		
Route / area	Round trip from Houston to San Antonio (I-10)		
Annual miles travelled per truck[1]	94,000		
Cumulative percent of trucks converted	n/a	4%	25%
Hydrogen			
Incremental H2 trucks converted	10	53	327
Number of filling stations (utilization)	2 stations total	2 (30%)	5 (37.5%)
Station dispenser count	1	2	2
Fueling rate per dispenser (kg/min)	3.6		
H2 filling station capital cost	$ 3,520,823	N/A: No additional stations	$ 7,613,723
H2 filling station operational cost ($/kg)	$3.24	$1.37	$0.38
Onboard hydrogen storage (kg)	60		
Fuel efficiency – hydrogen (mi/kg)	9.4		
Hydrogen from natural gas ($/kg)	$ 1.16	$ 1.04	$ 0.88
Hydrogen truck capital cost ($)	$ 310,247	$ 247,444	$ 219,115
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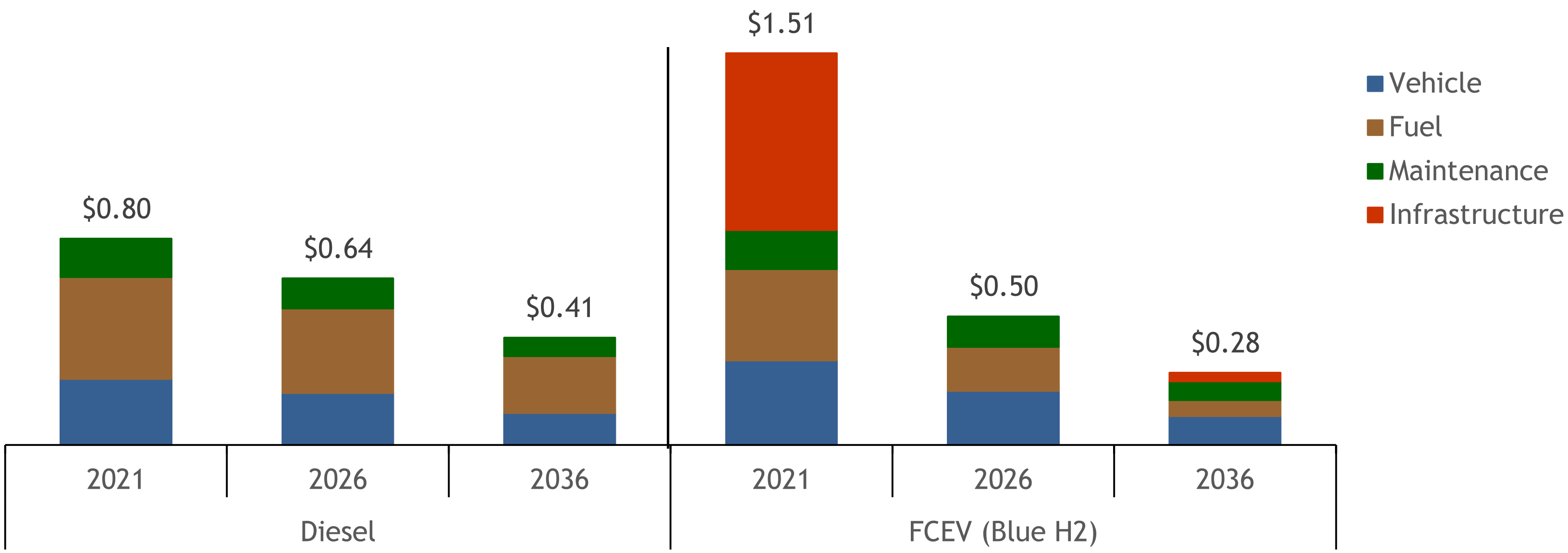
Diesel maintenance cost ($/mi)	$ 0.20		
Diesel truck capital cost ($)	$242,898		

Notes: (1) Miles driven per day per truck - 492, number of days driven per year – 235

Source: ANL: HDSRAM

Preliminary analysis shows H2 trucks are competitive with diesel along the I-10, San Antonio-Houston corridor

Total Cost of Ownership, diesel and H2 HDVs on I-10, $M/truck[1,2,3,4]



Assumes H2 is delivered to fueling stations via pipeline in the Expand (2026) and Rollout (2036) phases. Pipeline installation and costs are considered outside the scope of this evaluation and intended to serve both I-10 trucking market and export H2 from Houston, TX along I-10 to CA for LCFS

Notes: (1) 94,000 annual miles driven, total trucks in target area: 1,557 (2) station utilization: expand: 30%, rollout: 37.5% (3) pilot, expand and rollout phases last 10 yrs ea.; (4) YoY H2 truck capex reduction follows three phases (4%: '20-'25, 2.1%: '25-'30, 0.6% ea. yr. afterward)
Source: ANL: HDSRAM, EIA, KPMG analysis, ICCT: Infrastructure needs and costs for zero-emission trucks

Key assumptions:
TCO analysis for H2 transit buses vs. diesel for Houston METRO (1 of 2)

Assumption	Activate (2021)	Expand (2026)	Rollout (2036)
General			
Usage	High usage (20 hours/day)		
Number of buses converted	10	20	70
Cumulative percent of high usage buses converted	N/A	15%	50%
Route / area	High usage routes		
Daily miles driven	310		
Days / year	360		
Current fuel source	Diesel and CNG		
Capital cost (cost of debt)	5%		
Debt amortization period (years)	10		
Hydrogen			
Number of filling stations and utilization	1	2	10
Fuel economy	11.4 miles/kg		
Refueling station capex	$2.4m/station		
Refueling station opex	$2.59/kg	$0.76/kg	$0.56/kg
Bus capex - cost/bus	$1.2m		
Annual decrease in bus capex	1.4%		
Bus opex per mile cost	$0.48/mile		
Hydrogen from natural gas ($/kg)	$1.16		
Annual cost decrease in hydrogen from natural gas	1.9%		

Key assumptions:
TCO analysis for H2 transit buses vs. diesel for Houston METRO (2 of 2)

Assumption	Activate (2021)	Expand (2026)	Rollout (2036)
Diesel			
Bus capex – cost/bus		480,000	
Bus opex per mile cost		$0.88/mile	
Fuel economy		4.42 mpg	
Fuel price 2020		$2.81/gal	
Avg fuel price increase 2021-46		0.97%	
CO_2 emissions ton/mile		0.001872	

Key assumptions:
H2 seasonal storage economics (1 of 2)

Assumptions	Metric
General	
Gas turbine - MW generated per hour during high price in summer/fall, MW	240
Cost of debt (to annualize capital expenses), %	7 %
Gas turbine capacity factor, %	80 %
Price to store H2, geologic formation, $ / kwh	$ 0.02
Power price	
Avg. electricity price during low price hours (2019, Houston hub)	$ 26.43
Number of low price hours per day used to produce hydrogen, hours	9
Number of high priced hours per day used to put electricity on the grid, hours	6
Electricity generation source and H2 required	
H2 required to generate 1 MWh with H2 gas turbine, kg H2 / MWh	81.69

Source: H2city model, Barclays, Greater Houston partnership, Gencost 2018, EIA

Key assumptions:
H2 seasonal storage economics (2 of 2)

Assumptions	Metric
Electrolyzer	
Energy from each kg of H2, kWh	33.3
Energy efficiency, %	70%
Electrolyzer capital cost, $ / kW	$ 1,500
Electrolyzer capacity, MW	10
Electrolyzer - capacity factor, %	38%
Electrolyzer - lifecycle, years	15
Fixed opex per kw, $/kw	$ 28.17
Water required per kg of H2, H2O gal/ H2 kg	2.38
Yearly fixed cost of water supply, $ / year	$ 2,463
Variable cost of water, $ / H2O gal	$ 4.54
Stack life, years	15
Gas turbine	
Size, MW	506
Capex, $ / kw	$884.66
O&M - Fixed, $ / kw	$7.46
O&M - Variable, $ / kw	$5.25
Lifecycle, years	25
Carbon tax	
CO2 emitted per MWh with natural gas turbine, t CO2 / MWh	0.46

Source: H2city model, Barclays, Greater Houston partnership, Gencost 2018, EIA