Why Houston Will Be the Capital of a Low Carbon Energy World:
Creating a Carbon, Capture, Use, and Storage (CCUS) Hub

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Houston as a CCUS hub

Why CCUS?

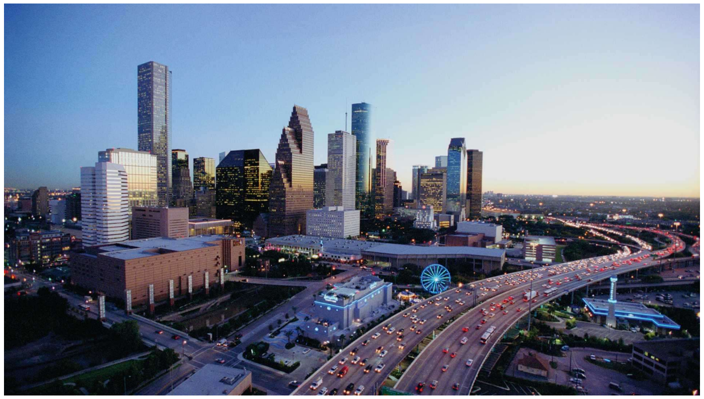
- CCUS essential to meet global climate targets
- Immediate emissions reductions from decarbonization
- Emission targets can't be achieved with clean energy alone
- Affordable, reliable, sustainable energy needed to reduce energy poverty

What Impacts?

- Long term sustainability of industries
- Set the stage for Houston as a decarbonization center of USA
- Globally recognized for energy skillset, knowledge, and technology
- Low carbon products advantage in global market

Why Houston?

- "Energy capital to sustainable energy capital"
- Infrastructure and scale suitable for "cluster" economics
- Vast, proximal geologic storage resources
- Energy companies strategies are shifting to "net-zero"



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Objectives and Findings

Objectives

- Develop a staged 3x10yr CCUS deployment analysis roadmap
- Utilize the NPC national analysis construct and regionalize for local impacts
- Analyze the emissions AND economic investment impact in the Houston Area
- Assess and position CCUS "optionality" to alternative geologic formations for both storage and EOR – as well as -for the extended energy producing network in the greater US Gulf Coast in all directions from Houston

FINDINGS

- Investment and risk hurdles will require "strategic investment"
- A mix of EOR and pure storage provides an investment portfolio approach for CCUS
- Current base of target geologies and infrastructure options are far greater than the stationary emissions in the 9 county Houston region – long term expansion impact
- Federal, state and local government policies must support/accelerate this transition

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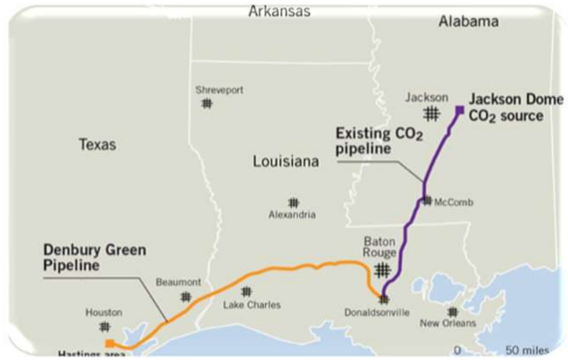
Key Challenges to Address in Project

Carbon Capture

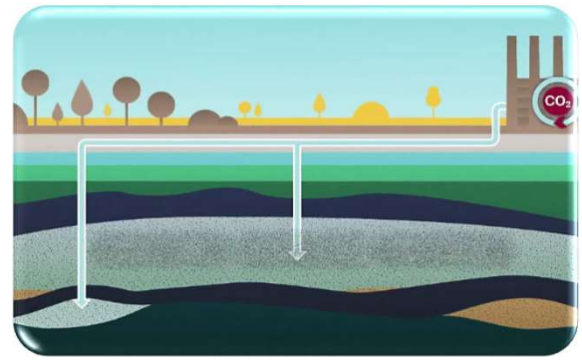
- Technology maturity
- Capture Cost of CO_2 (3/4 of total CCUS cost)
- Electricity cost for compression
- Separation cost to purify CO_2

Transportation



- Permits & Regulations
- Public acceptance
- Eminent Domain
- Cost of pipeline design and operating expense
- Infrastructure improvements

Storage



- Primacy
- Class 6 wells
- Low cost of oil
- Cost of surveillance (Liability for releases)
- Induced seismicity

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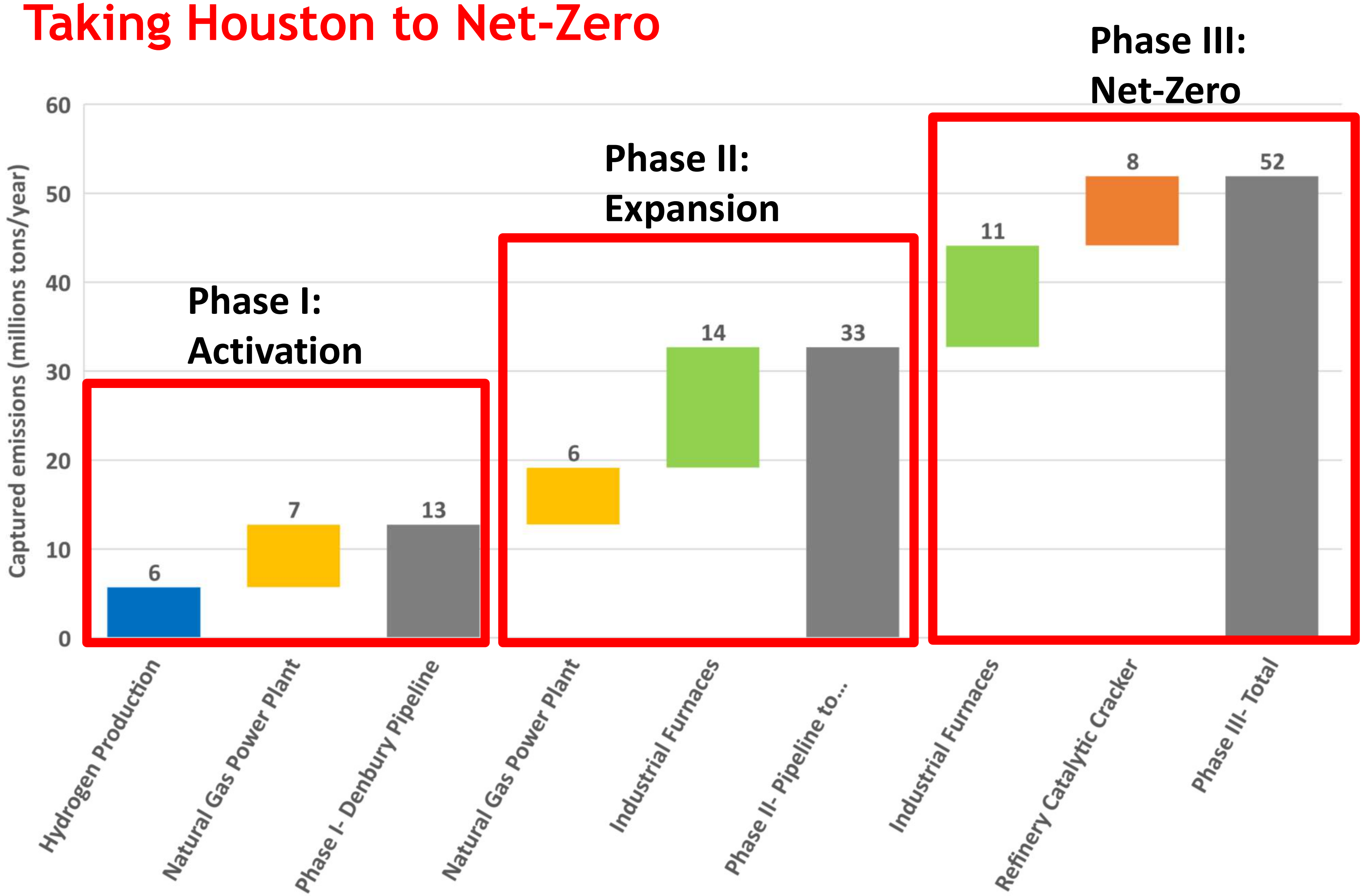
Taking Houston to Net-Zero



Phase I: Activation (2030)

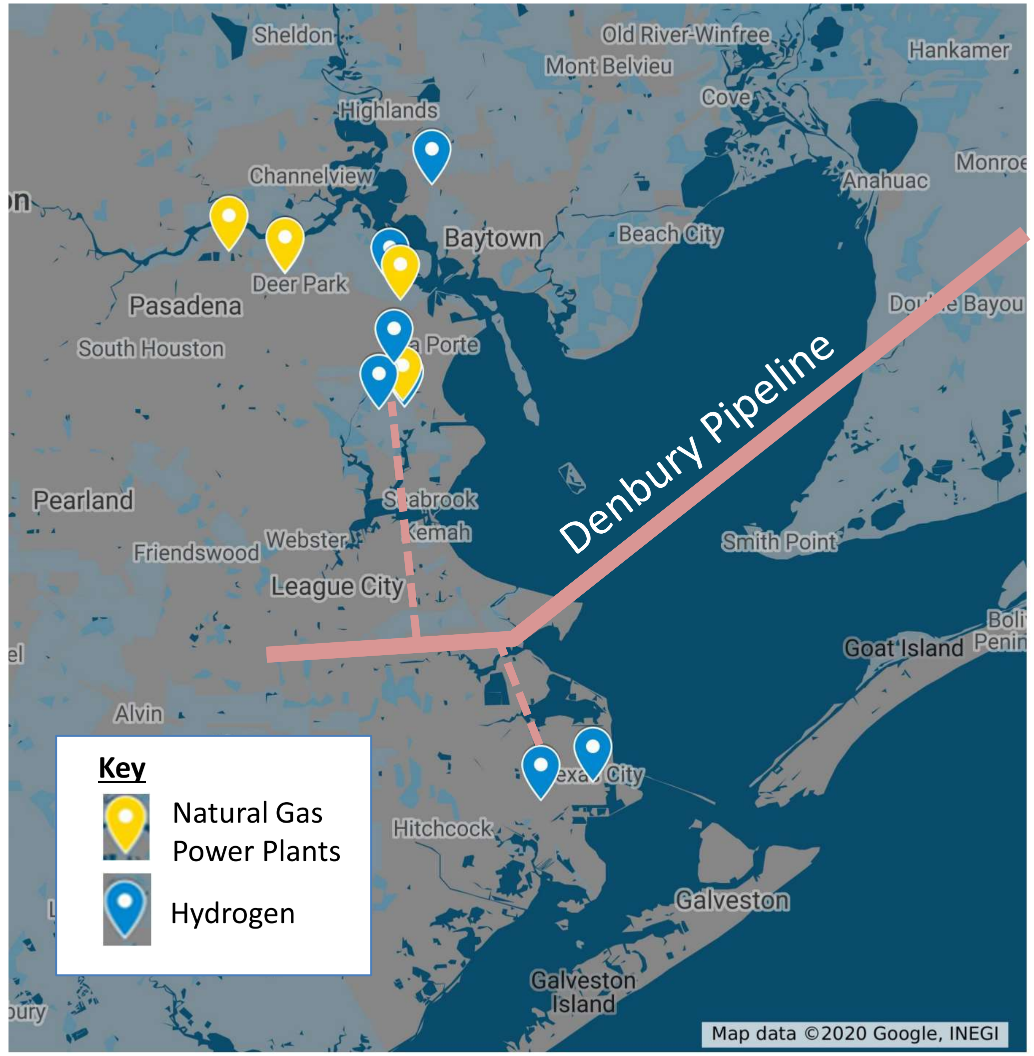
Capture

Facility type	Captured emissions (MM tons/yr)	Total investment (bil US$)
Hydrogen	5.7	$1.1
Natural gas power plants	7	$2.5

Transport

Pipeline	Available capacity (MM tons/yr)	Total investment (bil US$/yr)
Denbury	12.9	$0.12

- **Hydrogen emissions prioritized** due to cheaper capture cost.
- **Natural gas power plants second** due to increasing pressure from investors.
- **Denbury currently utilized at 1/3 capacity**.

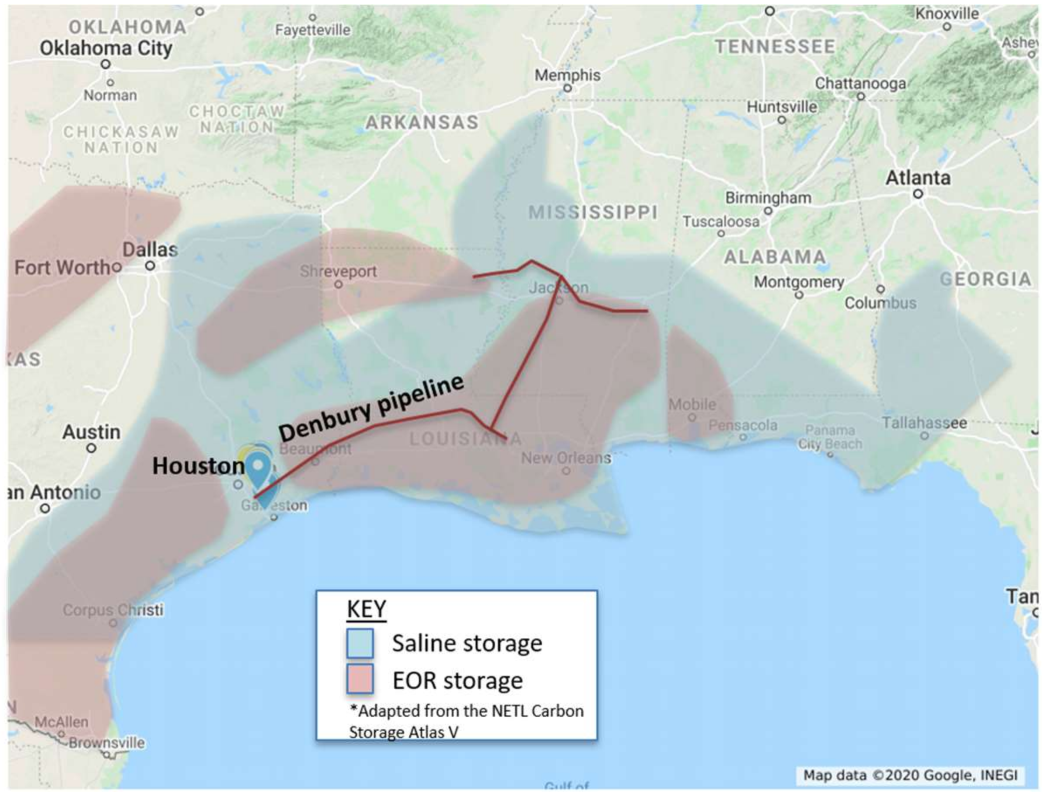


Phase I: Activation (2030)

Storage

Location	Available storage (bil tons)	Total investment (bil US$/yr)
Gulf Coast EOR	1.4	$0.12
Gulf Coast saline	1,500	

- **Significant EOR storage** is available along Gulf Coast in the form of disparate oil fields.
- Denbury has identified **multiple EOR fields along the pipeline's path**.
- **Saline storage is sufficient** to handle Denbury capacity **for 75 years.**



Phase I: Economic Model

Discounted cash flow model

- **Phase I only**
- Combined hydrogen/natural gas
- **Denbury pipeline**
- Toggle ratio of saline storage to EOR
- Outputs **NPV and IRR**

Assumptions

- **NPC** capture facility reference costs
- **Gaffney Cline** estimates for regional gas and electricity costs
- **Discount rate: 12%**
- Inflated oil, gas, and electricity annually

Scenarios

- **100% EOR scenario** and varied key inputs by +/-25%
- **100% saline scenario** and varied key inputs by +/-25%
- Oil price/45Q rate required for positive NPV

Hydrogen Capture

Inputs		units	Assumptions		units	Capex		units	Opex		units
Captured emissions	5,414,933	tons/year	bbls produced per metric ton of CO2 injected	2	barrels	Multiplier	13.54	X	Electricity usage	0.18	MWh/ton
Capacity per capture unit installed	400,000	tons/year	Project life	20	years	Capture capex (total)	1,063,289,854	$	Electricity price	10	$/MWhr
Online percentage	100%	%	45Q rate (EOR)	35	$/metric ton	1st year capex	20%	%	Gas usage	2.55	MMBtu/ton
% saline storage	0%	%	45Q rate (saline)	50	$/metric ton	2nd year capex	50%	%	Gas price	2	$/MMBtu
			WTI oil price	40	$/bbl	3rd year capex	30%	%	Opex, non-energy, annua	2%	% of capex
			Inflation	3%	%	Avg Hydrogen capex	78,545,000		Midstream tariff	10	$/ton
			Tax rate	21%	%	Tie-in pipeline cost per n	$ 2,000,000.00	$/mile	Storage cost	10	$/ton
			Discount rate	12%	%	Length of tie-in line	151	miles			
			Depreciation	7	years	Total cost of tie-in line	$ 302,000,000.00	$			

Natura…

Inputs		units	Capex	
Captured emissions	7,040,654	tons/year	Multiplier	4.68
Capacity per capture	1,504,290	tons/year	Capture capex (tota	2,468,925,574
Online percentage	100%	%	1st year capex	20%
% saline storage	0%	%	2nd year capex	50%
			3rd year capex	30%
			Avg Nat Gas Power	527,505,000

	Oil Price (infated annually)	$40.00	$41.00	$42.03	$43.08	$44.15	$45.26	$46.39	$47.55	$48.74	$49.95	$51.20	$52.48	$53.80	$55.14	$56.52	$57.93	$59.38
	Gas price (inflated annually)	$2.00	$2.05	$2.10	$2.15	$2.21	$2.26	$2.32	$2.38	$2.44	$2.50	$2.56	$2.62	$2.69	$2.76	$2.83	$2.90	$2.97
	Electricity price (inflated annually)	$10.00	$10.25	$10.51	$10.77	$11.04	$11.31	$11.60	$11.89	$12.18	$12.49	$12.80	$13.12	$13.45	$13.79	$14.13	$14.48	$14.85
	Years	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Revenue	45Q Revenue (saline storage)	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
	45Q Revenue (EOR storage)	$0.00	$0.00	$0.00	$435,945,548.85	$435,945,548.85	$435,945,548.85	$435,945,548.85	$435,945,548.85	$435,945,548.85	$435,945,548.85	$435,945,548.85	$435,945,548.85	$435,945,548.85	$435,945,548.85	$435,945,548.85	$435,945,548.85	$435,945,548.85
	Petroleum revenue	$0.00	$0.00	$0.00	$1,073,064,399.01	$1,099,891,008.99	$1,127,388,284.21	$1,155,572,991.32	$1,184,462,316.10	$1,214,073,874.00	$1,244,425,720.85	$1,275,536,363.87	$1,307,424,772.97	$1,340,110,392.29	$1,373,613,152.10	$1,407,953,480.90	$1,443,152,317.93	$1,479,231,125.87
	Total Revenue	$0.00	$0.00	$0.00	$1,509,009,947.86	$1,535,836,557.84	$1,563,333,833.06	$1,591,518,540.17	$1,620,407,864.95	$1,650,019,422.85	$1,680,371,269.70	$1,711,481,912.72	$1,743,370,321.82	$1,776,055,941.14	$1,809,558,700.95	$1,843,899,029.75	$1,879,097,866.78	$1,915,176,674.72
Capex	Hydrogen capture capex	$212,657,970.77	$531,644,926.93	$318,986,956.16	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
	Nat gas power plant capex	$493,785,114.72	$1,234,462,786.80	$740,677,672.08	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
	Tie-in line capex	$100,666,666.67	$100,666,666.67	$100,666,666.67	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Opex	Electricity (Hydrogen)	$0.00	$0.00	$0.00	$10,496,323.77	$10,758,731.86	$11,027,700.16	$11,303,392.66	$11,585,977.48	$11,875,626.91	$12,172,517.59	$12,476,830.53	$12,788,751.29	$13,108,470.07	$13,436,181.82	$13,772,086.37	$14,116,388.53	$14,469,298.24
	Gas (Hydrogen)	$0.00	$0.00	$0.00	$29,739,584.00	$30,483,073.60	$31,245,150.44	$32,026,279.21	$32,826,936.19	$33,647,609.59	$34,488,799.83	$35,351,019.83	$36,234,795.32	$37,140,665.20	$38,069,181.83	$39,020,911.38	$39,996,434.16	$40,996,345.02
	Opex, non-energy (Hydrogen)	$0.00	$0.00	$0.00	$21,265,797.08	$21,265,797.08	$21,265,797.08	$21,265,797.08	$21,265,797.08	$21,265,797.08	$21,265,797.08	$21,265,797.08	$21,265,797.08	$21,265,797.08	$21,265,797.08	$21,265,797.08	$21,265,797.08	$21,265,797.08
	Electricity (Natural gas)	$0.00	$0.00	$0.00	$11,265,045.98	$11,265,045.98	$11,265,045.98	$11,265,045.98	$11,265,045.98	$11,265,045.98	$11,265,045.98	$11,265,045.98	$11,265,045.98	$11,265,045.98	$11,265,045.98	$11,265,045.98	$11,265,045.98	$11,265,045.98
	Gas (Natural gas)	$0.00	$0.00	$0.00	$39,427,660.94	$39,427,660.94	$39,427,660.94	$39,427,660.94	$39,427,660.94	$39,427,660.94	$39,427,660.94	$39,427,660.94	$39,427,660.94	$39,427,660.94	$39,427,660.94	$39,427,660.94	$39,427,660.94	$39,427,660.94
	Opex, non-energy (Natural gas)	$0.00	$0.00	$0.00	$49,378,511.47	$49,378,511.47	$49,378,511.47	$49,378,511.47	$49,378,511.47	$49,378,511.47	$49,378,511.47	$49,378,511.47	$49,378,511.47	$49,378,511.47	$49,378,511.47	$49,378,511.47	$49,378,511.47	$49,378,511.47
	Transport tariff	$0.00	$0.00	$0.00	$124,555,871.10	$124,555,871.10	$124,555,871.10	$124,555,871.10	$124,555,871.10	$124,555,871.10	$124,555,871.10	$124,555,871.10	$124,555,871.10	$124,555,871.10	$124,555,871.10	$124,555,871.10	$124,555,871.10	$124,555,871.10
	Storage cost	$0.00	$0.00	$0.00	$124,555,871.10	$124,555,871.10	$124,555,871.10	$124,555,871.10	$124,555,871.10	$124,555,871.10	$124,555,871.10	$124,555,871.10	$124,555,871.10	$124,555,871.10	$124,555,871.10	$124,555,871.10	$124,555,871.10	$124,555,871.10
	EBITDA (Rev-capex-opex)	-$807,109,752.16	-$1,866,774,380.40	-$1,160,331,294.91	$1,098,325,282.41	$1,124,145,994.69	$1,150,612,224.78	$1,177,740,110.62	$1,205,546,193.61	$1,234,047,428.67	$1,263,261,194.61	$1,293,205,304.69	$1,323,898,017.53	$1,355,358,048.19	$1,387,604,579.62	$1,420,657,274.33	$1,454,536,286.40	$1,489,262,273.79
	Depreciation	$547,745,061.07	$547,745,061.07	$547,745,061.07	$547,745,061.07	$547,745,061.07	$547,745,061.07	$547,745,061.07										
	EBIT (Rev-OPEX-Depreciation)	-$1,354,854,813.23	-$2,414,519,441.47	-$1,708,076,355.98	$550,580,221.35	$576,400,933.63	$602,867,163.71	$629,995,049.55	$1,205,546,193.61	$1,234,047,428.67	$1,263,261,194.61	$1,293,205,304.69	$1,323,898,017.53	$1,355,358,048.19	$1,387,604,579.62	$1,420,657,274.33	$1,454,536,286.40	$1,489,262,273.79
	NOPLAT (EBIT*(1-Tax Rate))	-$1,070,335,302.45	-$1,907,470,358.76	-$1,349,380,321.22	$434,958,374.86	$455,356,737.57	$476,265,059.33	$497,696,089.15	$952,381,492.95	$974,897,468.65	$997,976,343.74	$1,021,632,190.71	$1,045,879,433.85	$1,070,732,858.07	$1,096,207,617.90	$1,122,319,246.72	$1,149,083,666.26	$1,176,517,196.29
	FCF	-$1,329,699,993.54	-$3,226,499,678.10	-$1,961,966,555.06	$982,703,435.93	$1,003,101,798.63	$1,024,010,120.40	$1,045,441,150.22	$952,381,492.95	$974,897,468.65	$997,976,343.74	$1,021,632,190.71	$1,045,879,433.85	$1,070,732,858.07	$1,096,207,617.90	$1,122,319,246.72	$1,149,083,666.26	$1,176,517,196.29
	PV of FCF	-$1,187,232,137.09	-$2,572,145,789.30	-$1,396,489,040.76	$624,525,799.24	$569,186,899.56	$518,795,395.40	$472,904,483.98	$384,650,911.64	$351,557,800.52	$321,321,673.43	$293,694,842.01	$268,451,200.89	$245,384,335.59	$224,305,797.36	$205,043,530.32	$187,440,437.24	$171,353,071.65
	Project NPV	$113,543,909.91																
	IRR	12%																

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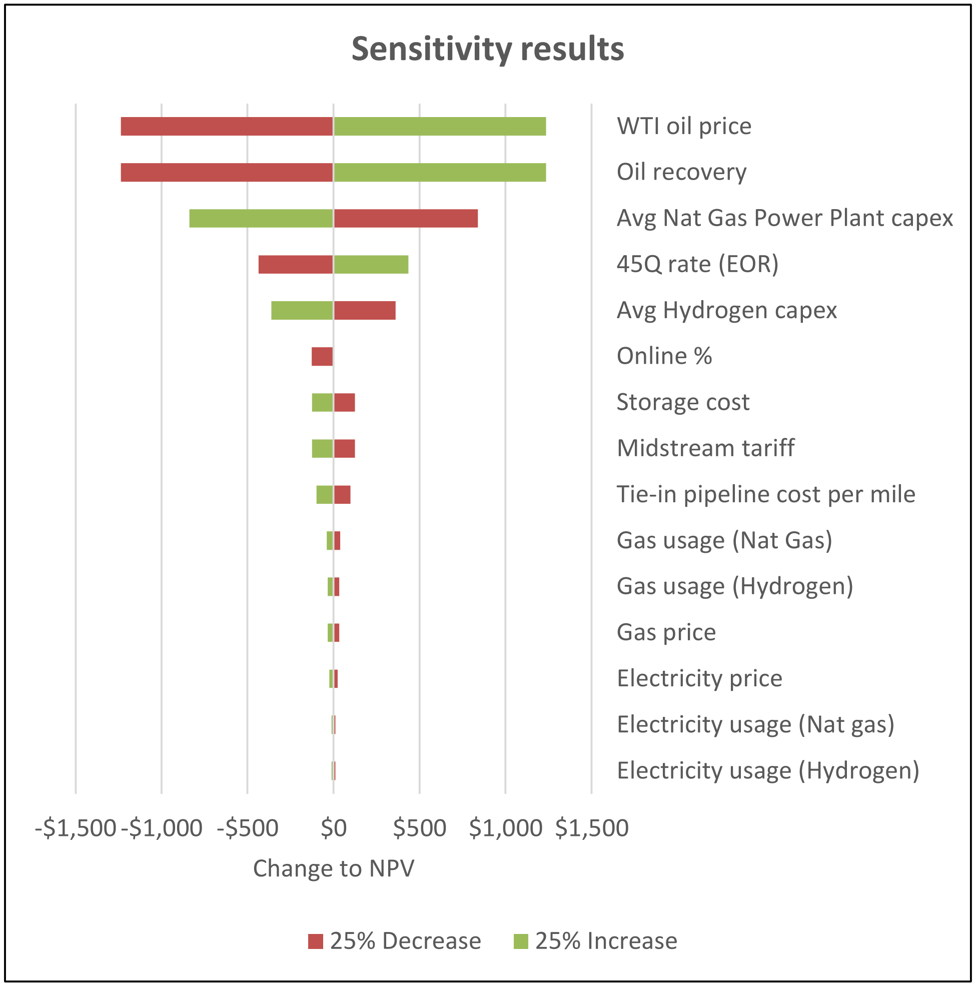
Phase I: Economic Model Results

Combined hydrogen and natural gas power plant model – 100% EOR

Sensitivity 1		
Base Case Assumptions (100% EOR)		
Online %	100	
bbls produced per metric ton of CO2	2	barrels
45Q rate (EOR)	$35	$/metric ton
45Q rate (saline)	$50	$/metric ton
WTI oil price	$40	$/bbl
Avg Hydrogen capex	$78,545,000.00	$/unit
Avg Nat Gas Power Plant capex	$527,505,000.00	$/unit
Tie-in pipeline cost per mile	$2,000,000.00	$/mile
Length of tie-in line	151	miles
Electricity usage (Hydrogen)	0.18	MWh/ton
Electricity usage (Nat gas)	0.16	MWh/ton
Electricity price	$10	$/MWhr
Gas usage (Hydrogen)	$2.55	MMBtu/ton
Gas usage (Nat Gas)	$2.80	MMBtu/ton
Gas price	$2	$/MMBtu
Opex, non-energy, annual	0.02	% of capex
Midstream tariff	$10.00	$/ton
Storage cost	$10.00	$/ton
NPV	$ 113,543,909.91	
IRR	12%	

- **Project can be NPV positive with 12% IRR today**.....however
- **US40/bbl price required for 20 years** for project with high risk potential
- Most influential parameters include: **oil price, recovery factor, nat gas capex, and 45Q rate**



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Key Take-aways

- **Phase I (present to 2030):**
  - **Focus on low cost strategic CO_2 Houston emissions:** 5.7million tons/yr from Hydrogen SMR
    7 million tons/yr from Natural Gas Power
  - **Transport on existing/available Denbury pipeline:** 13 million ton/yr available capacity
  - **Gulf coast accessible geologic storage:** 1.4 Billion tons for EOR and 1.5 Trillion tons of saline
  - **EOR most economically attractive with current tax credits BUT with Highest Risk**
  - **Parameters needed for overall positive system NPV: (with 12% all equity hurdle)**
    - 100% EOR storage requires $40/bbl oil price PLUS 45Q credit of $35/ton
    - 100% saline storage only requires 45Q Tax credit significantly above current $50/ton
- **Phase II (2040):**
  - **Expand capture to include: 6.4 million tons/yr** from Natural Gas Power Plant
    13.5 **million tons/yr** from Industrial Processes – Refining and Pet Chem
  - **Build pipelines to the East/Central Texas:** 20-30 million tons/yr available capacity at $500 million cost (250 miles X US$2 million/mile). On and offshore geologic target zones
  - **East/Central Texas available storage:** 3.6 billion tons for EOR and 500 billion tons of saline
- **Phase III (2050):**
  - **Expand capture to include: 11.4 million** tons/yr from Industrial Furnaces
    7.8 million tons/yr from Refinery Catalytic Cracker
  - **Build pipeline to the Permian:** 20 million tons/yr available capacity at US$1 billion cost (500 miles X US$2 million/mile)
  - **Permian available geologic storage:** 4.8 billion tons of EOR and 1 trillion tons of saline

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Gaffney Cline

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Thank you!

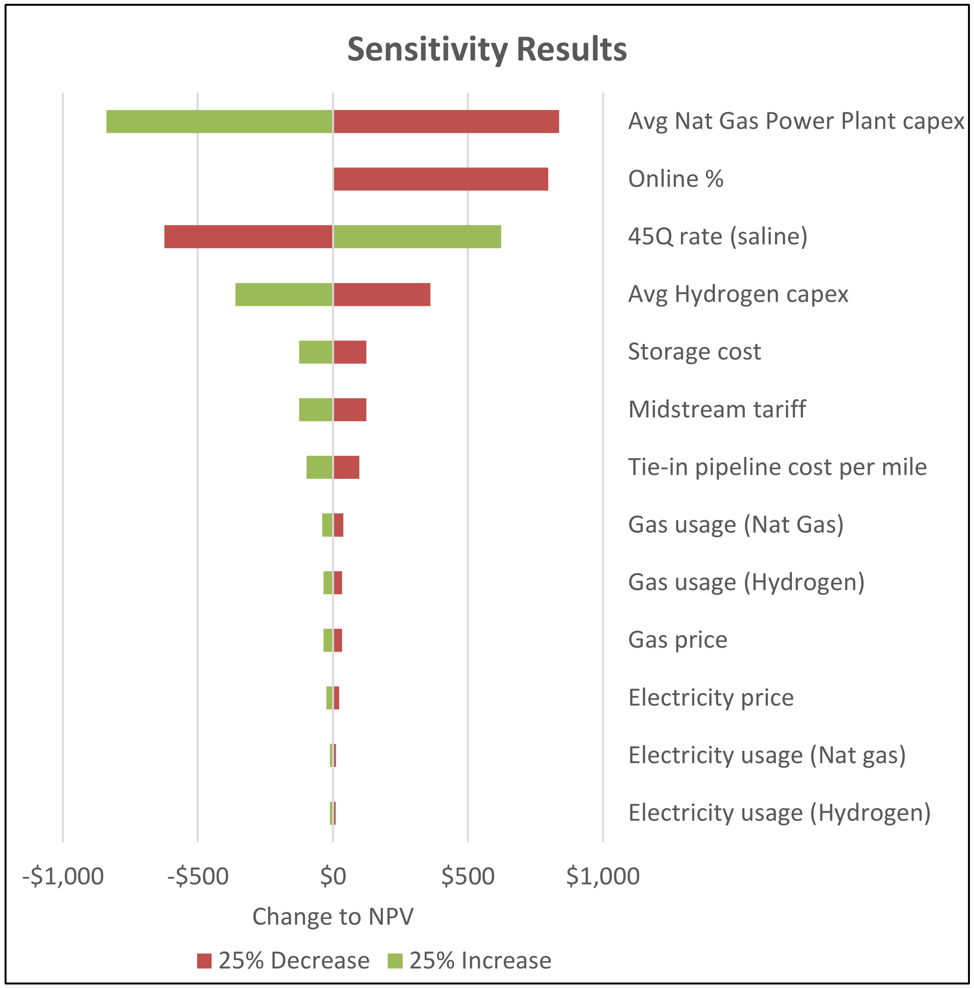
Appendix

Phase I: Economic Model Results

Combined hydrogen and natural gas power plant model – 100% storage

Sensitivity 2		
Base Case Assumptions (100% Saline)		
Online %	100	
bbls produced per metric ton of CO2 i	2	barrels
45Q rate (EOR)	$35	$/metric ton
45Q rate (saline)	$50	$/metric ton
WTI oil price	$40	$/bbl
Avg Hydrogen capex	$78,545,000	$/unit
Avg Nat Gas Power Plant capex	$527,505,000	$/unit
Tie-in pipeline cost per mile	$2,000,000	$/mile
Length of tie-in line		miles
Electricity usage (Hydrogen)	0.18	MWh/ton
Electricity usage (Nat gas)	0.16	MWh/ton
Electricity price	$10	$/MWhr
Gas usage (Hydrogen)	2.55	MMBtu/ton
Gas usage (Nat Gas)	2.8	MMBtu/ton
Gas price	$2	$/MMBtu
Opex, non-energy, annual	0.02	% of capex
Midstream tariff	$10	$/ton
Storage cost	$10	$/ton
NPV	$ (3,583,733,634.47)	
IRR	-3%	

- **Project is grounded in 12% all equity return criteria….and….**
- **US$+100/Ton 45Q price needed** today for positive project @12% all equity
- Most influential parameters include: **capex, online %, 45Q rate, hydrogen and NGCC capex**



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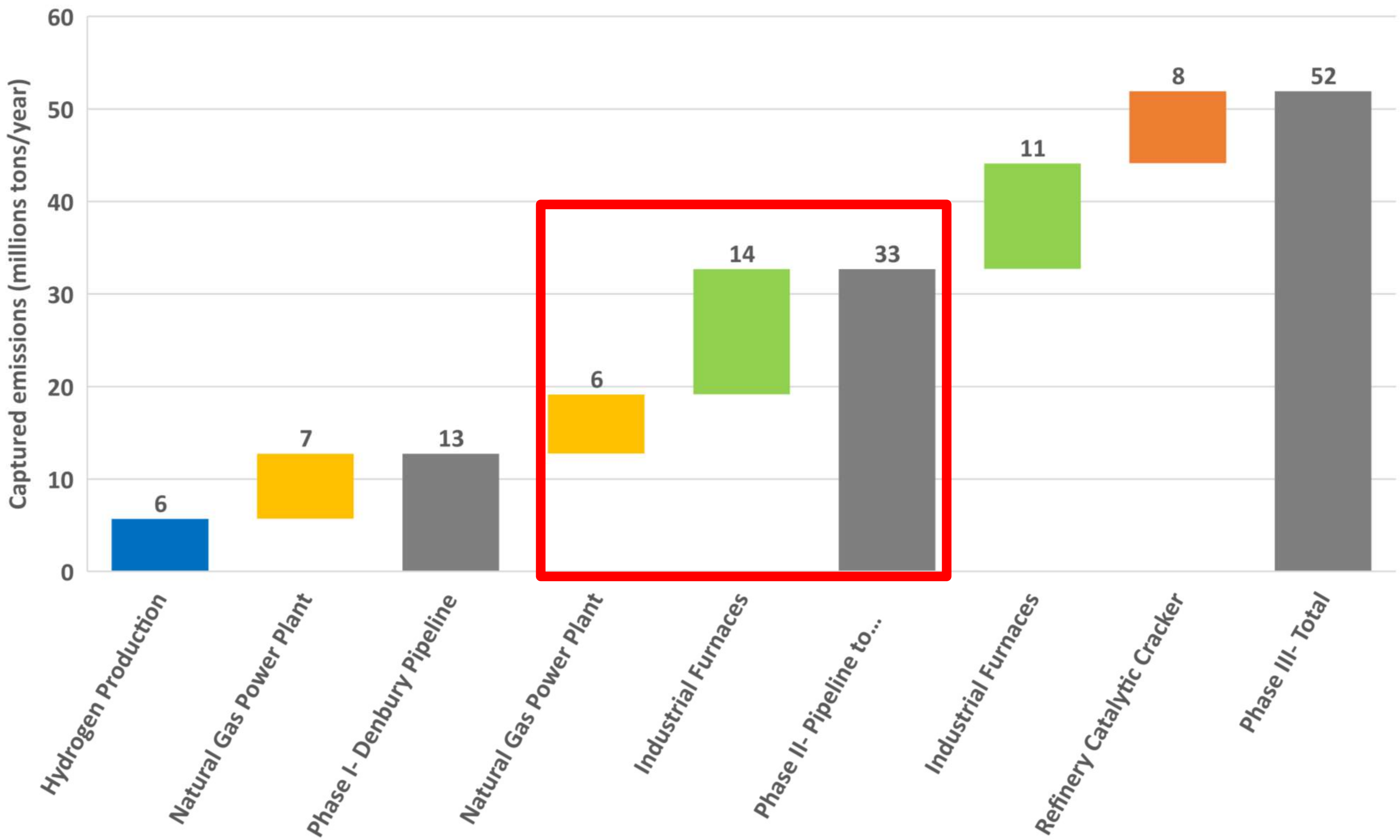
Phase II: Expansion - FW Basin and Offshore



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Phase II: Expansion (2040)

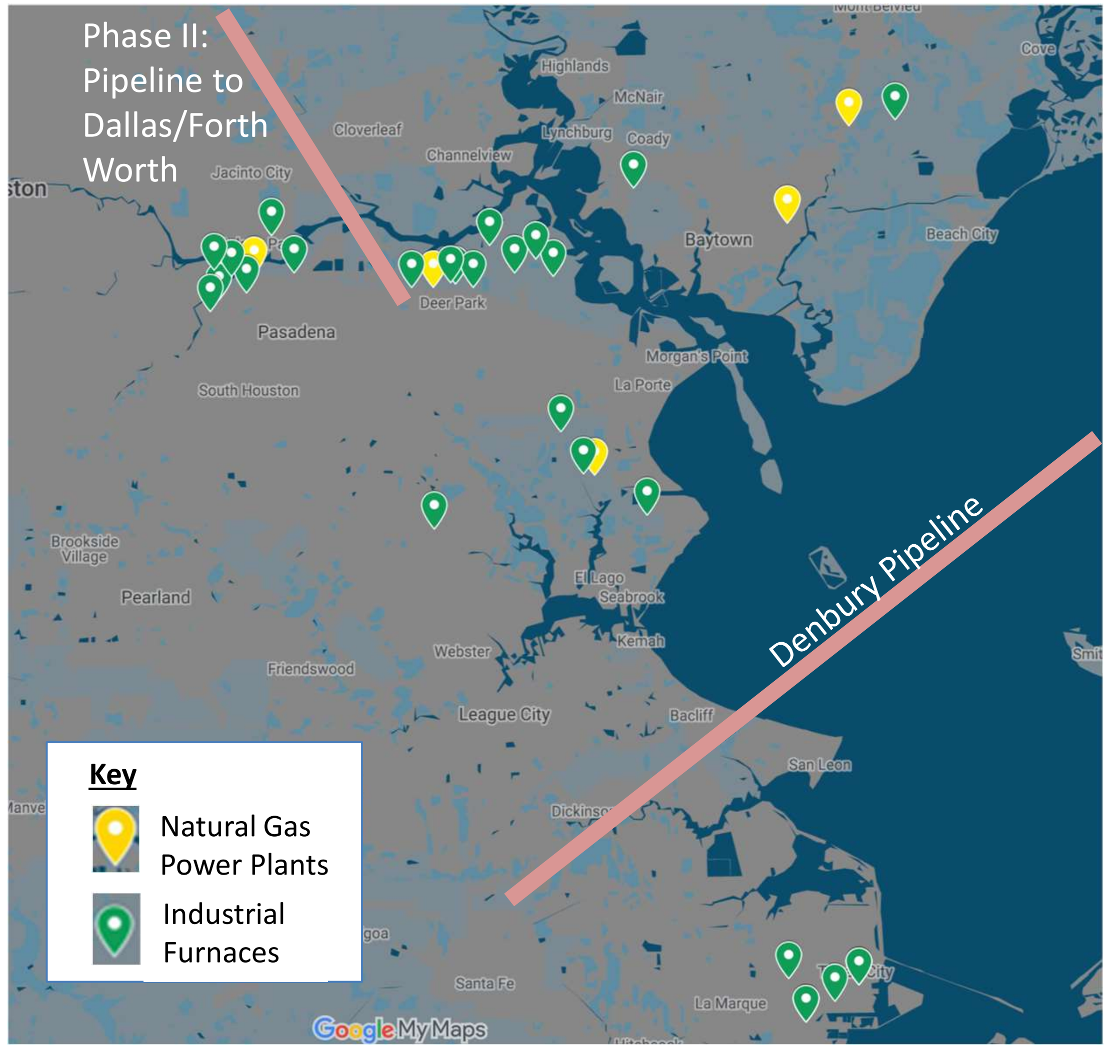
Capture

Facility Type	Captured emissions (MM tons/yr)	Total Investment (bil US$)
Natural Gas Power Plant	6.4	2.2
Industrial Furnaces	13.5	6.4

Transport

Pipeline	Available capacity (MM tons/yr)	Total Investment (bil US$)
East/Central Texas	20	$0.5

- **Build 250-Mile** Houston -to- East/Central Texas **Pipeline**
- **Industrial Furnaces** are included to expand annual capture of CO_2
- Additional **Natural Gas Power Plants** are involved in the expansion of capacity transportation



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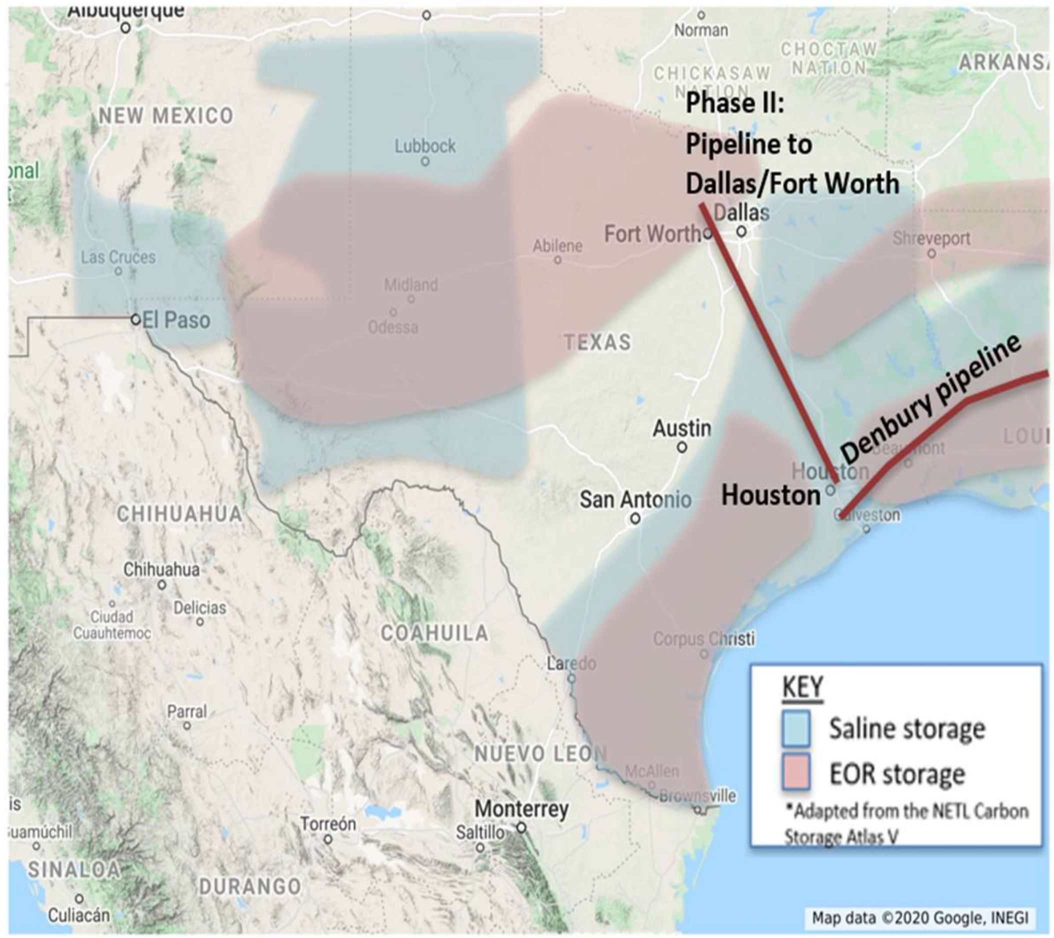
Phase II: Expansion (2040)

Storage

Location	Available storage (bil tons)	Total Investment (bil US$/yr)
East/Central Texas EOR	3.6	TBD
East/Central Texas saline	501	

- **EOR and Saline storage** is available in East/Central Texas
- **Leveraging the demand for CO_2 EOR**, offering a relatively larger **economic benefit**



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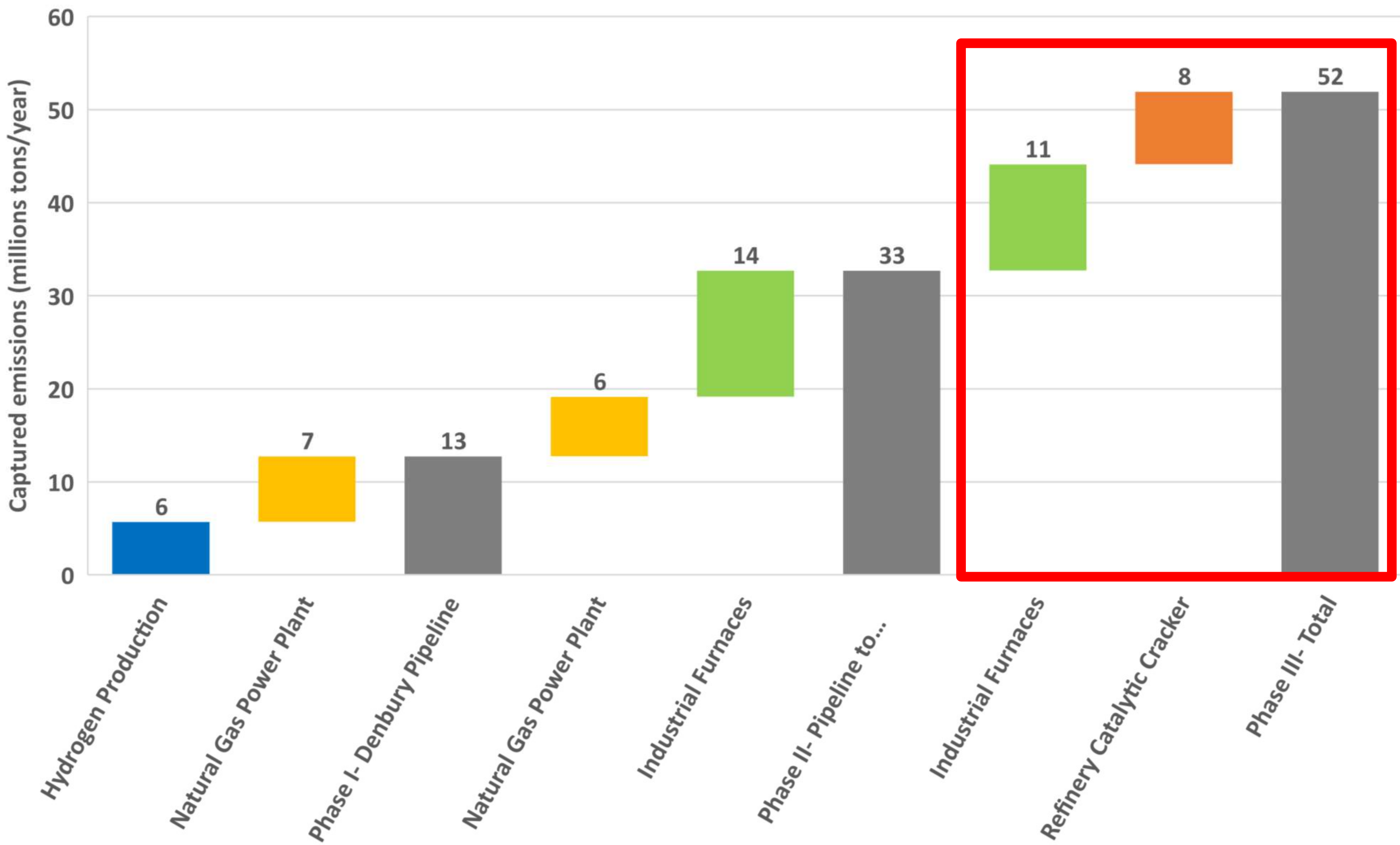
Phase III: At-Scale - Taking Houston to Net Zero



Phase III: At-Scale (2050)

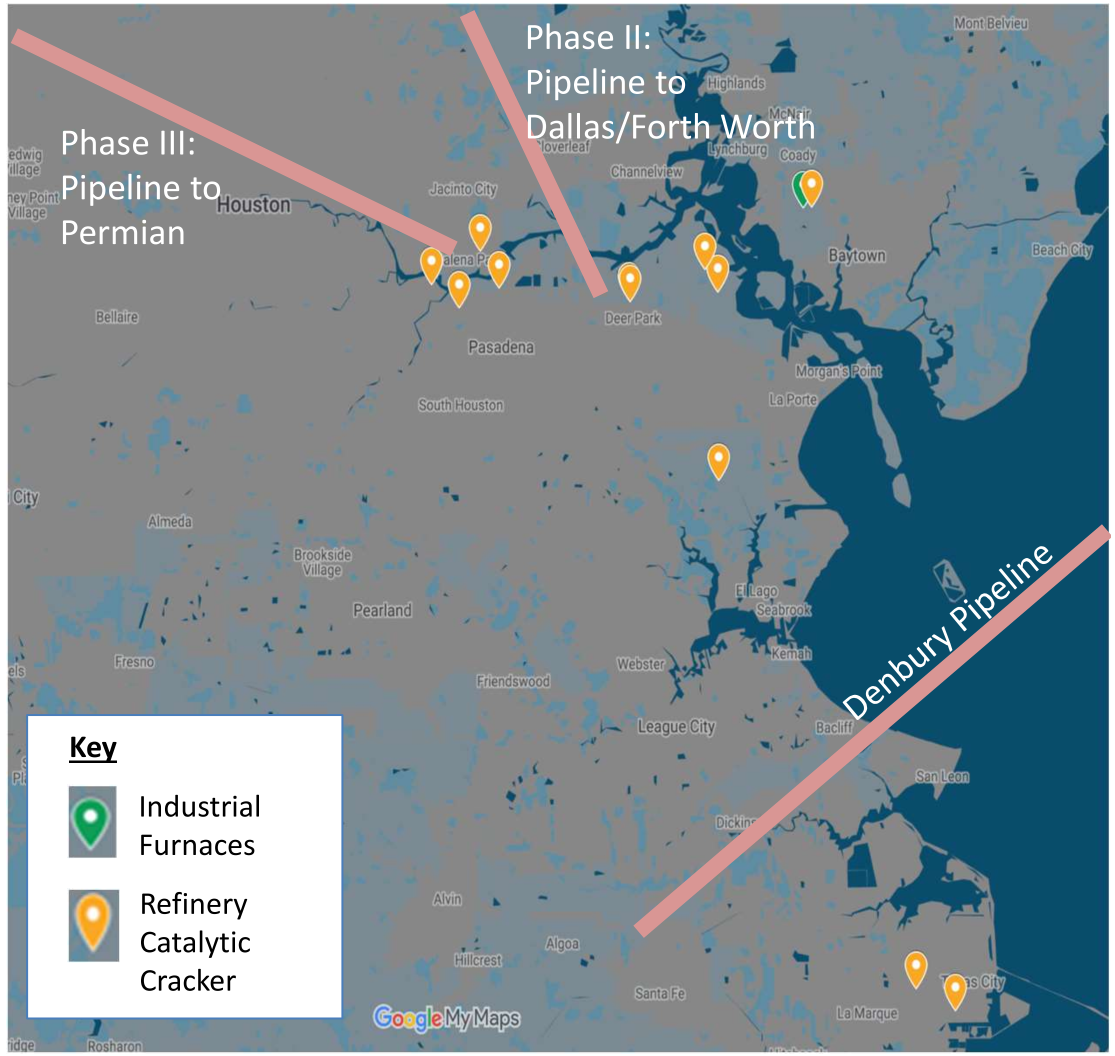
Capture

Facility Type	Captured emissions (MM tons/yr)	Total Investment (bil US$)
Industrial Furnaces	11.4	2.8
Refinery Catalytic Cracker	7.8	1.4

Transport

Pipeline	Available capacity (MM tons/yr)	Total Investment (bil US$)
Permian	20	$1

- **Build 500-Mile** Houston -to- Permian **Pipeline**
- **Refinery Catalytic Cracker** are included to expand annual capture of CO_2
- Projected pipeline from Houston to the Permian Basin will **help with the economic feasibility of both carbon capture and pipeline projects**

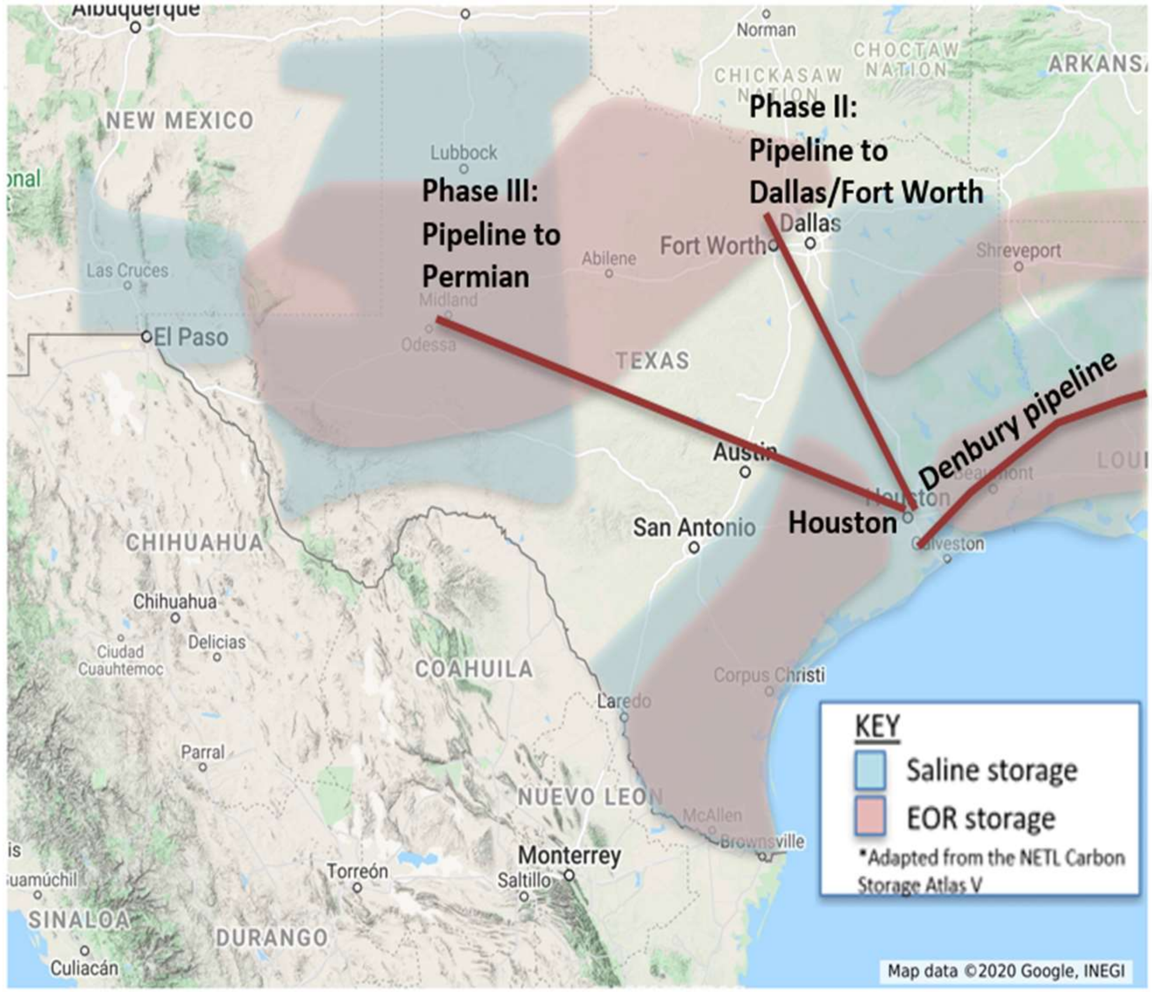


Phase III: At-Scale (2050)

Storage

Location	Available storage (bil tons)	Total Investment (bil US$/yr)
Permian EOR	4.8	TBD
Permian saline	1000	

- **Large-scale of EOR and saline storage** available in the Permian Basin
- Storage capacity in the Permian will permit to **achieve net-zero in carbon goal**



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Key Take-aways

- **Phase I (present to 2030):**
  - **Focus on low cost strategic CO_2 Houston emissions:** 5.7million tons/yr from Hydrogen SMR
    7 million tons/yr from Natural Gas Power
  - **Transport on existing/available Denbury pipeline:** 13 million ton/yr available capacity
  - **Gulf coast accessible geologic storage:** 1.4 Billion tons for EOR and 1.5 Trillion tons of saline
  - **EOR most economically attractive with current tax credits BUT with Highest Risk**
  - **Parameters needed for overall positive system NPV: (with 12% all equity hurdle)**
    - 100% EOR storage requires $40/bbl oil price PLUS 45Q credit of $35/ton
    - 100% saline storage only requires 45Q Tax credit significantly above current $50/ton
- **Phase II (2040):**
  - **Expand capture to include:** **6.4 million tons/yr** from Natural Gas Power Plant
    13.5 **million tons/yr** from Industrial Processes – Refining and Pet Chem
  - **Build pipelines to the East/Central Texas:** 20-30 million tons/yr available capacity at $500 million cost (250 miles X US$2 million/mile). On and offshore geologic target zones
  - **East/Central Texas available storage:** 3.6 billion tons for EOR and 500 billion tons of saline
- **Phase III (2050):**
  - **Expand capture to include:** **11.4 million** tons/yr from Industrial Furnaces
    7.8 million tons/yr from Refinery Catalytic Cracker
  - **Build pipeline to the Permian:** 20 million tons/yr available capacity at US$1 billion cost (500 miles X US$2 million/mile)
  - **Permian available geologic storage:** 4.8 billion tons of EOR and 1 trillion tons of saline

Why Houston Will Be the Capital of a Low Carbon Energy World:
Becoming a Global Hydrogen Hub

Matt Hoffman, Zujajah Fatima, Katherine Nguyen

KPMG/CHF working team: Andy Steinhubl, Todd Blackford, Josh Gresham, Brett Perlman

October 9th 2020

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

Project approach & methodology

- Summarize how Houston area can leverage its unique assets to enter clean blue and green H2 production
  - Assimilated decarbonization strategies
  - Assessed case studies across the value chain
- Identify and prioritize the most advantaged H2 end markets to create new blue and green chains
  - Targeted analytical studies
- 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

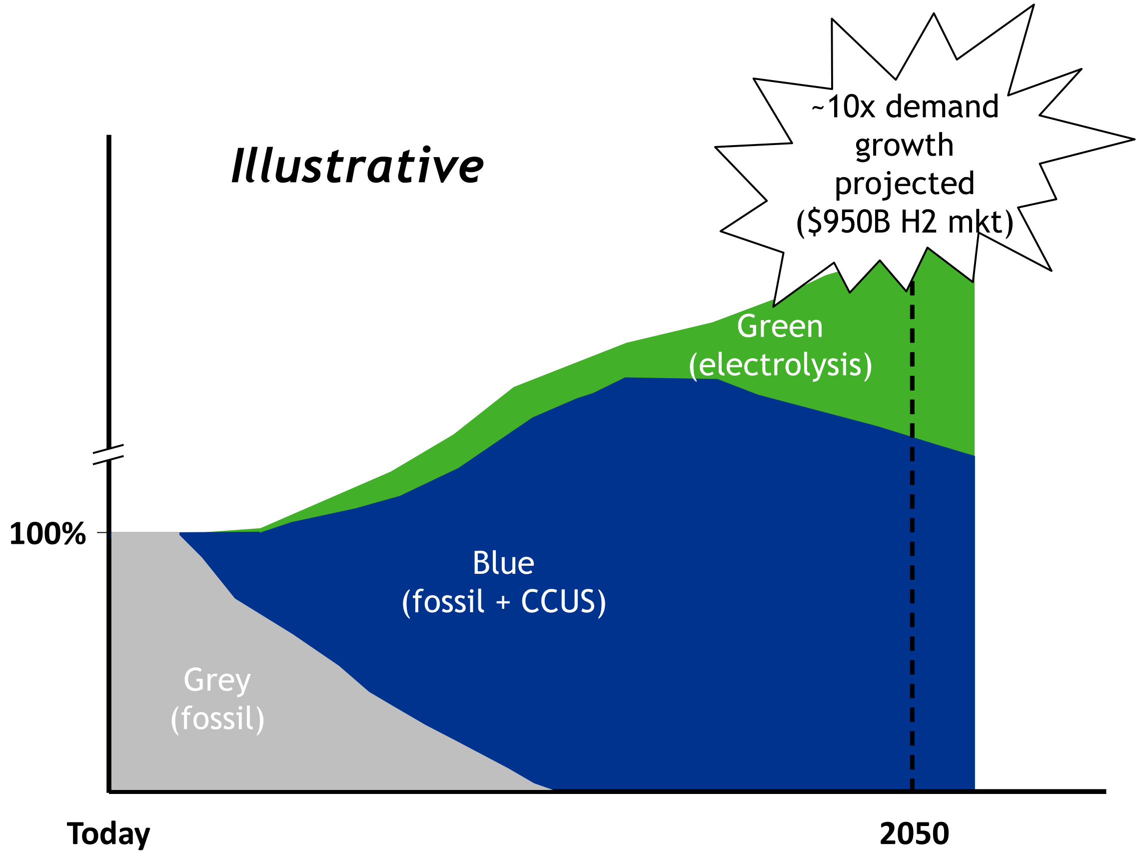
Key Findings

- **Global decarbonization momentum is growing, catalyzing substantial global H2 gas market expansion of $800 billion by 2050, and a $2.5 Trillion total market including related H2 technologies**
- **The Houston area is poised to drive significant H2 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
- **Further, the Houston area has substantial regional, domestic, and global supply leadership potential through parlaying its scale and cost advantages across the hydrogen and carbon chains**
- **Unleashing Houston's near and long-term H2 market opportunities will require targeted public policy and funding support**

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

Decarbonization is catalyzing rapid H2 market expansion, and strategies are emerging to capture the opportunity

Hydrogen demand and mix over time



Source: Barclays, HSBC, Hydrogen Council

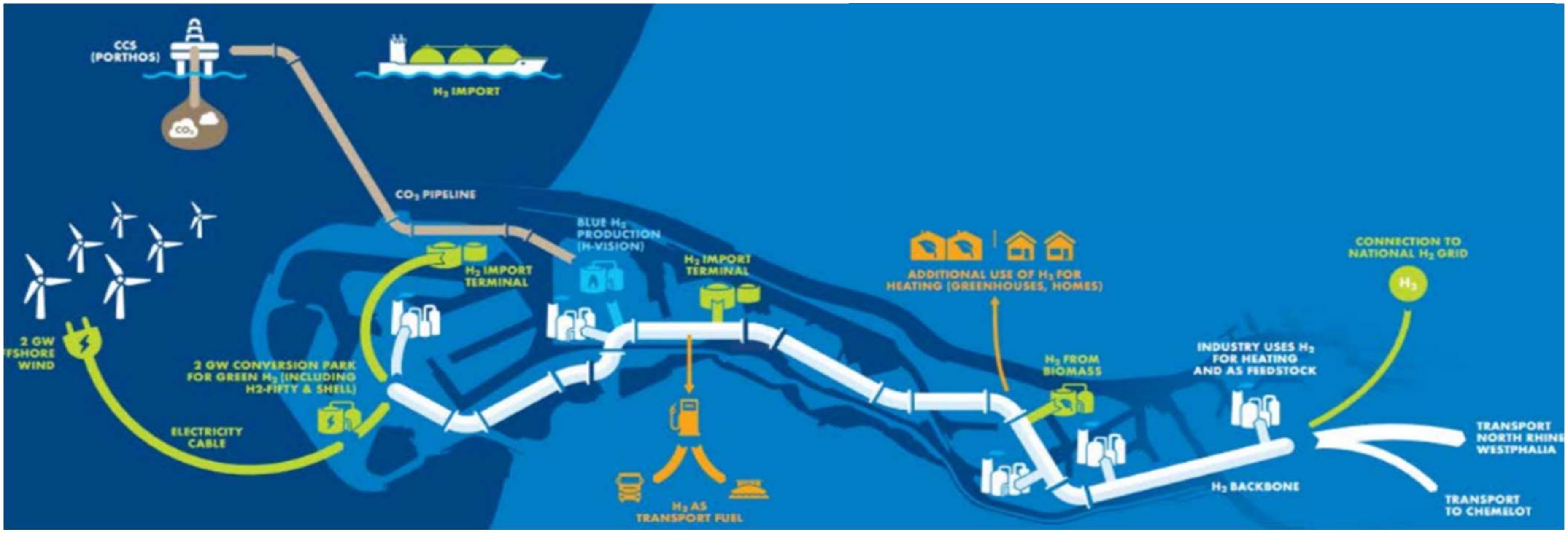
Localized Drivers

- 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

For example, 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)

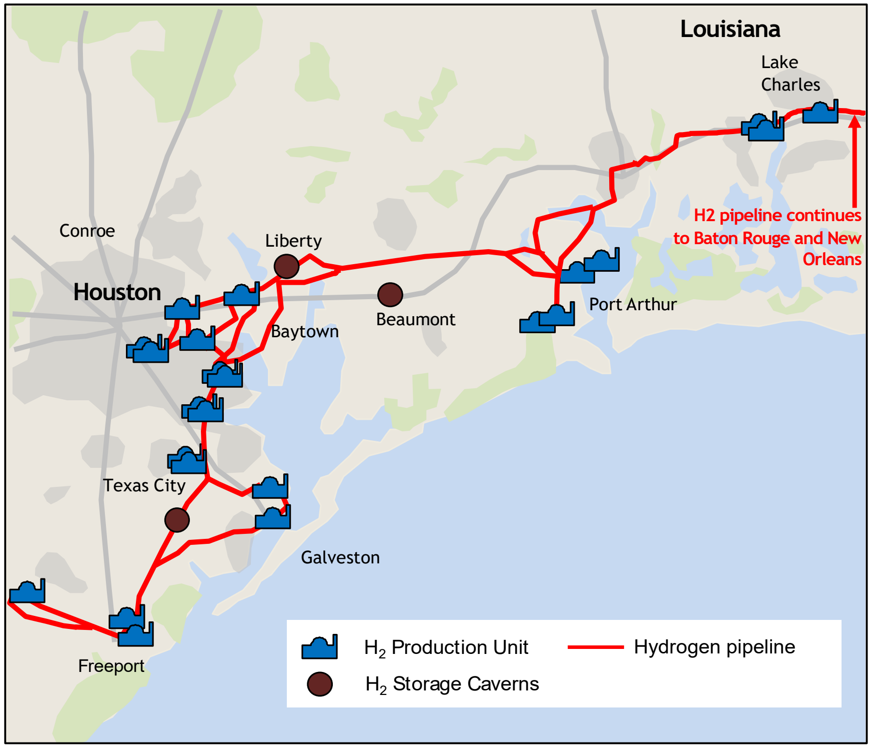
To – energy hub of tomorrow…

- 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 anchors a world leading H2 system, with multiple scale and cost advantages

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*

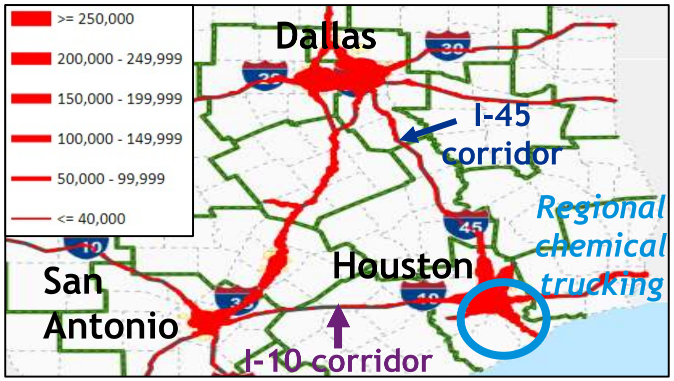
TX Gulf Coast H2 system advantages[1,2,3]

- **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

In the near-term, the existing system can be leveraged to kick-start the H2 economy by using H2 in heavy duty trucks

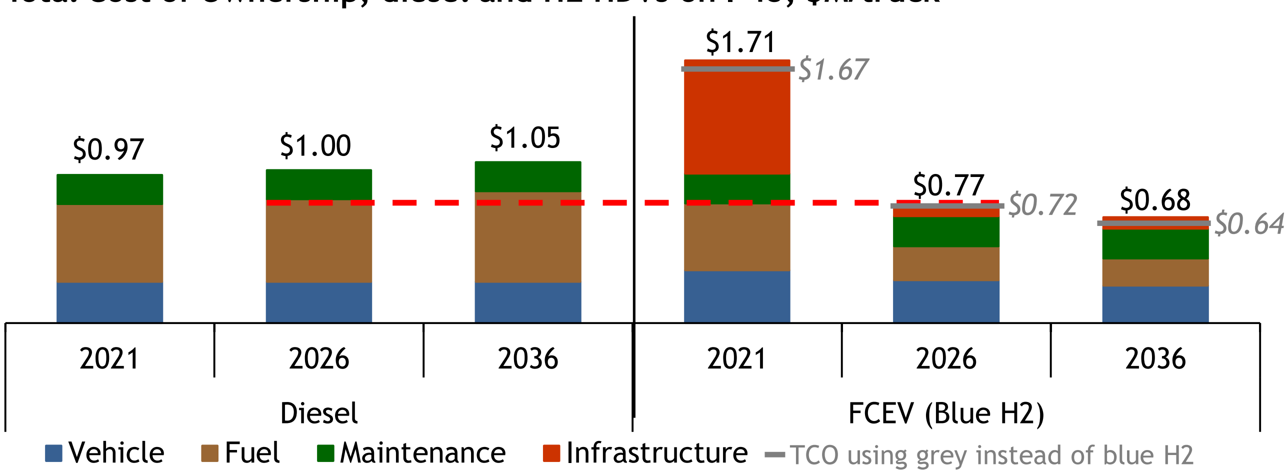
Texas truck traffic, 2018



Several local and regional heavy trucking markets

- I-45: offers long-haul advantage over battery electric vehicles (BEVs) and potential to link to Dallas / central US distribution hub
- I-10: offers long-haul advantage over BEVs and potential to synergize with a pipeline to the W. Coast to tap the Calif. Low Carbon Fuel Standard (LCFS)market
- Regional trucking: potential easier demonstration, though BEV may be advantaged for shorter trips where payload/capacity less of focus

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



- Lower H2 (SMR) TCO:
  - Low H2 cost
  - Increasing diesel costs
  - Infrastructure scale economies
- 17% well to wheel emissions reduction for grey H2 vs. diesel

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

Houston could exploit multiple advantages to become a clean H2 export leader as the global market expands

Case for Houston as global blue export capital

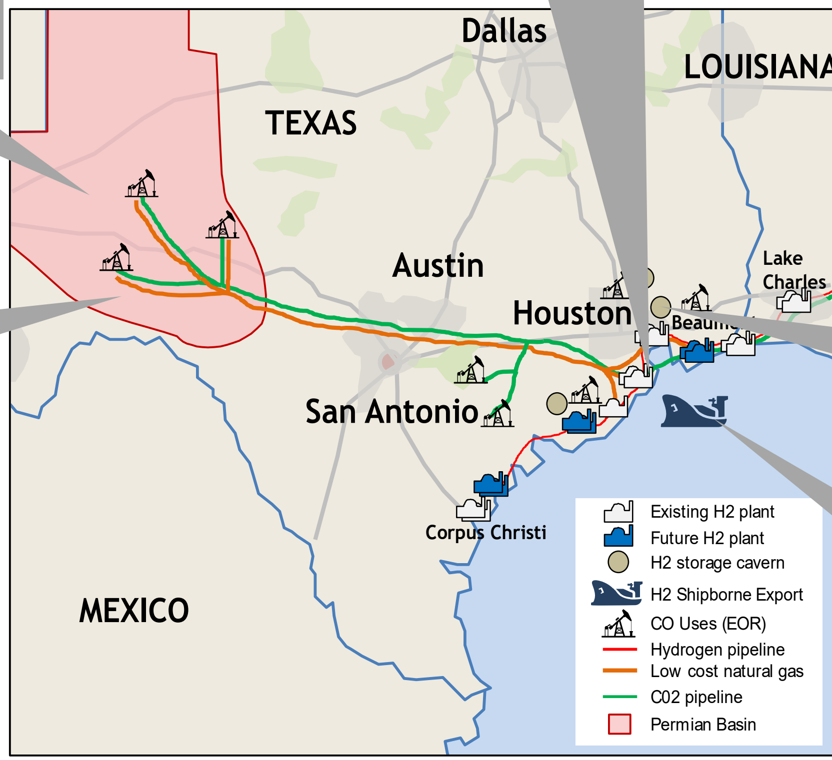
Opportunity to create low-cost, at-scale CCUS system; 95% clean H2

World scale in-place H2 production capacity

Global low- cost natural gas feedstock

Global H2 storage and transport infrastructure leader

Leading commodity export port



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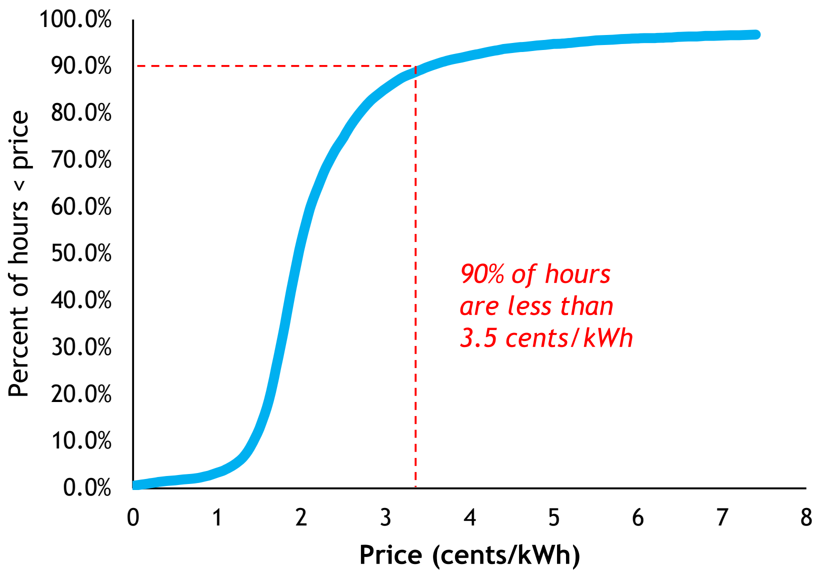
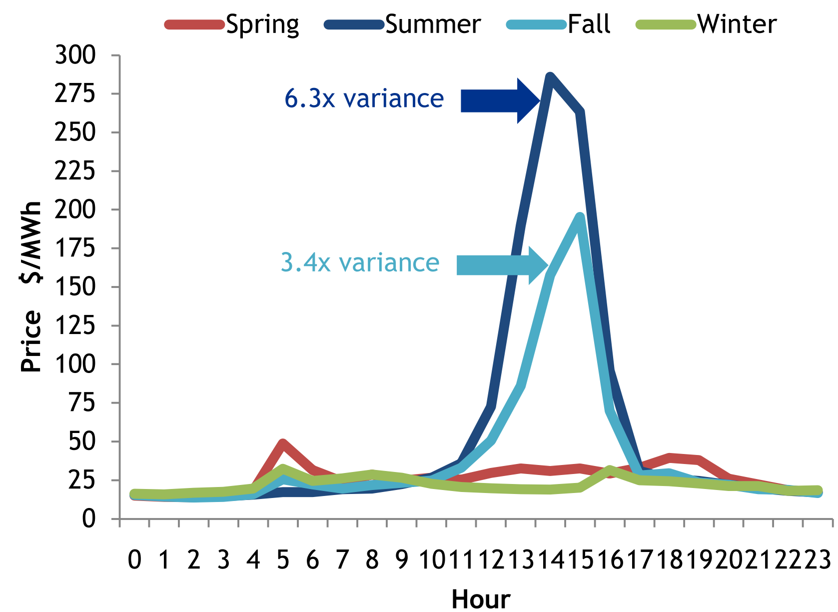
Additionally, TX has power price and storage advantages that could support a green H2 industry build out

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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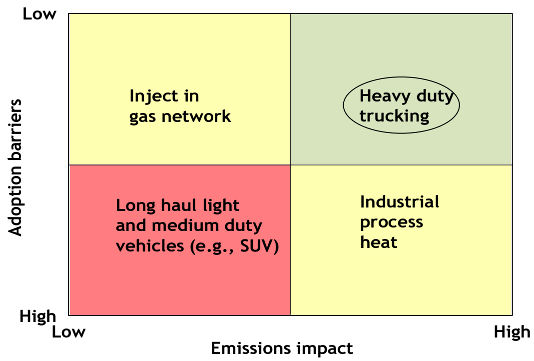
Four immediate initiatives, with targeted policy/funding, will activate Houston's H2 growth potential

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

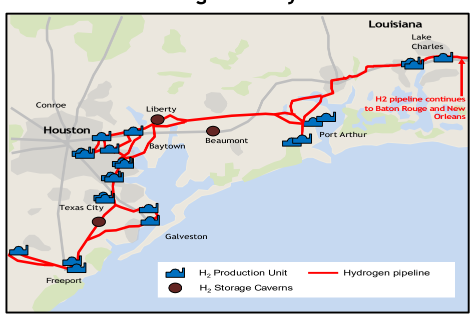
Prioritization of blue markets



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

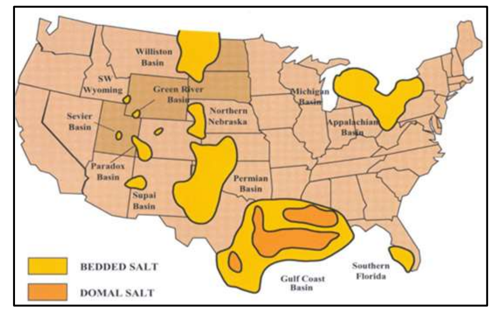


Activate

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

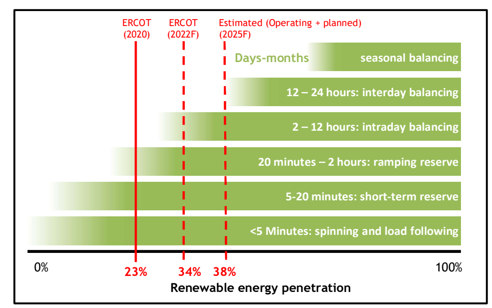
US salt cavern storage



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

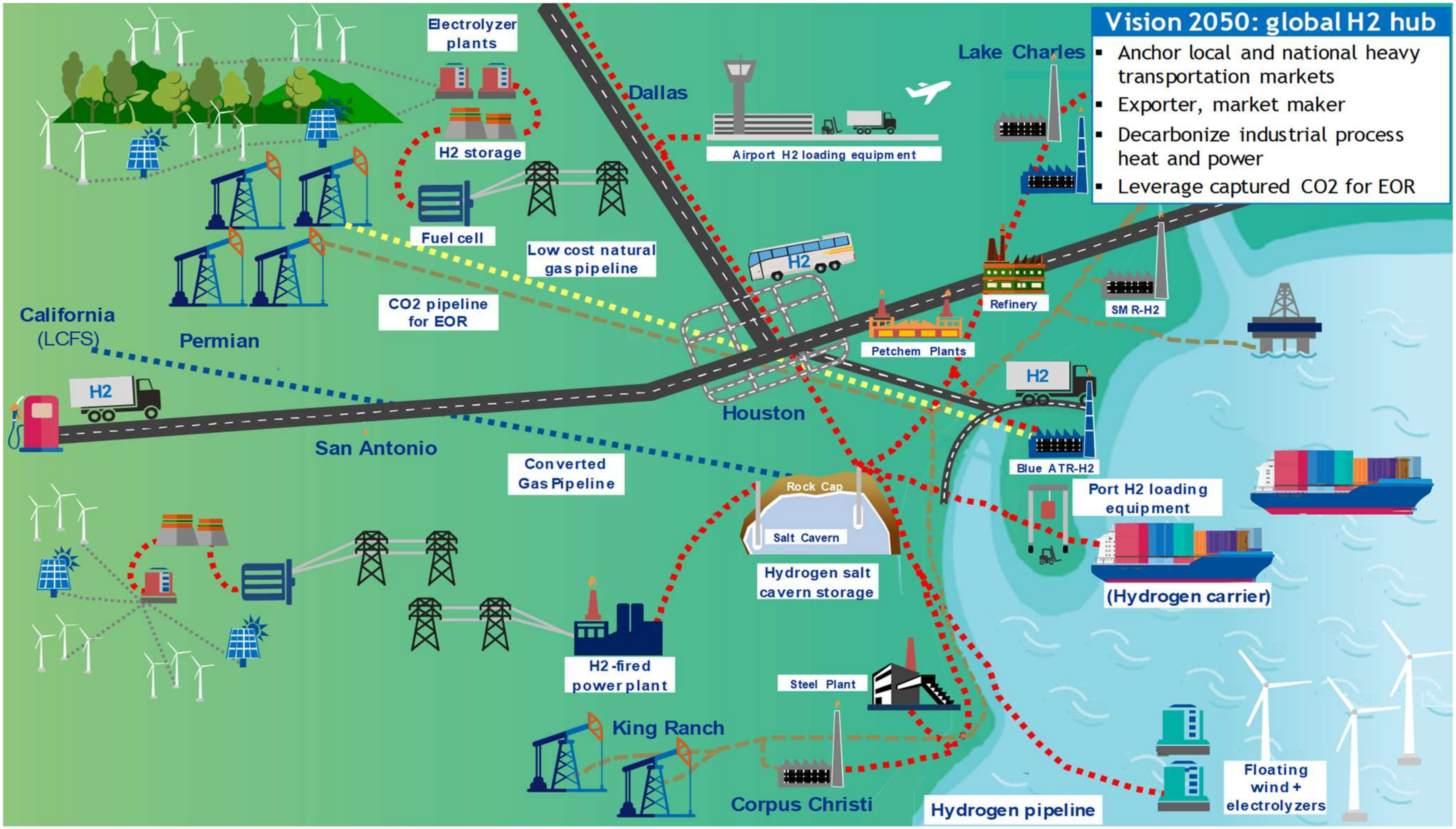


Policy and funding

- 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

Potential Houston '2050 vision': local, national, and global flywheel for H2 supply



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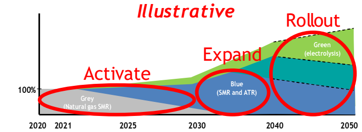
A potential game plan leveraging regional advantages to scale blue and green H2 toward this vision was developed

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

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UH / KPMG working team: Matt Hoffman, Zujajah Fatima, Katherine Nguyen, Andy Steinhubl, Todd Blackford, Josh Gresham

Thank You!

Why Houston Will Be the Capital of a Low Carbon Energy World:
Pathways Towards a NET ZERO Grid

Hamzah Ansari, Cameron Barrett, Turner Harris.
Nishchala Naini

Faculty Mentor: Greg Bean

October 8th, 2020

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PATHWAYS TOWARD NET ZERO GRID – KEY FINDINGS

- ERCOT (the power grid representing 90% of Texas electricity demand) has already achieved a significant reduction in carbon intensity, and renewable growth trends indicate continued progress in this regard
- ERCOT is well positioned for continued growth in renewable energy supply, and Houston can be expected to play a leading role in this effort
- However, the pathway to a net zero grid faces three key challenges:
  - The mismatch between renewable production and load profiles, coupled with the physical reality that power supply must equal demand on a near-instantaneous basis
  - Seasonal and diurnal variability of renewable production, and
  - Existence of must-run CO2 emitting generation, acting to "crowd out" renewable supply during periods of low demand
- Absent energy storage, continued addition of renewable resources will ultimately lead to extended periods of renewable curtailment, dampening financial returns on renewable investment and inhibiting further grid decarbonization
- Energy storage technologies can capture and store episodically excess renewable supply and allow carbon free supply to approach 90%, although the financial return for such technologies is inevitably diminished as storage capacity grows – ultimately constraining further investment in storage
- Adoption of green hydrogen production can provide an effective storage solution for balancing supply and demand over seasonal periods; the electrolysis process can utilize excess renewable production when it is generated, and the resulting hydrogen can be stored for multi-day and seasonal periods
- Additionally, green hydrogen would leverage both existing natural gas storage/transport/power generation infrastructure, as well as existing brown hydrogen infrastructure
- Finally, achievement of net zero carbon emissions from the power grid is technically feasible, but the law of diminishing returns ensures that the marginal cost to eliminate the last few percentages of grid carbon emissions will be very high – potentially far in excess of the cost to reduce emissions from other sectors of the economy

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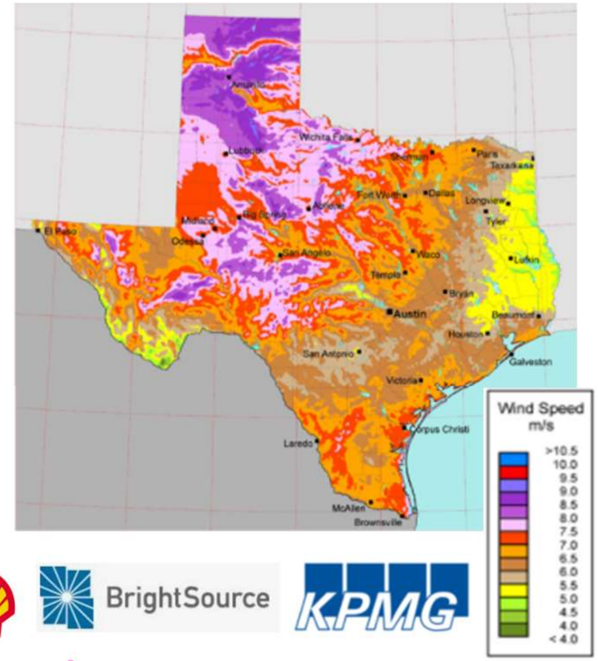
TEXAS WELL POSITIONED FOR EXPANSION OF RENEWABLES AND ENERGY STORAGE

Texas is well positioned for expansion of renewables and energy storage

- Top-tier wind and solar resources
- Independent power grid; ERCOT is not connected to Eastern and Western interconnections, and is largely regulated by state authority
- ERCOT's operation and optimization of ~$10 billion/year energy market is world-class
- One of the largest unregulated retail power markets in the world – over 22 million Texans can choose from over 200 retail electric providers
- Extensive pipeline, natural gas, and transmission infrastructure
- Suitable salt geology to support energy storage in the Gulf Coast, east Texas, and the Panhandle

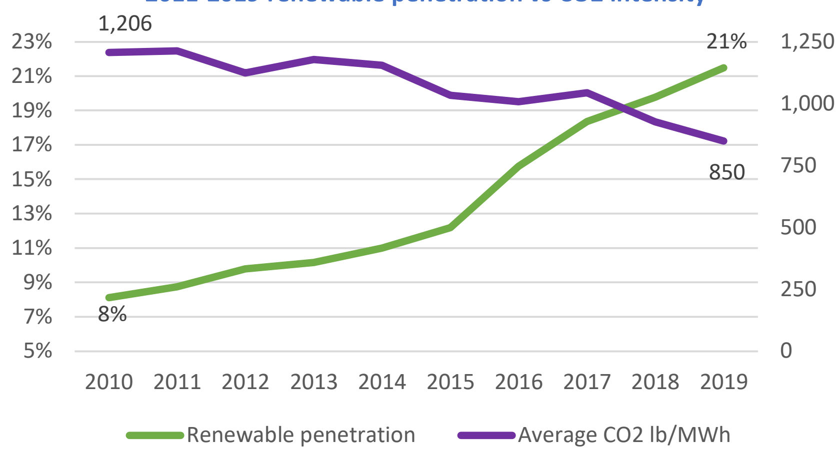


Houston community can cement a leadership role in grid decarbonization

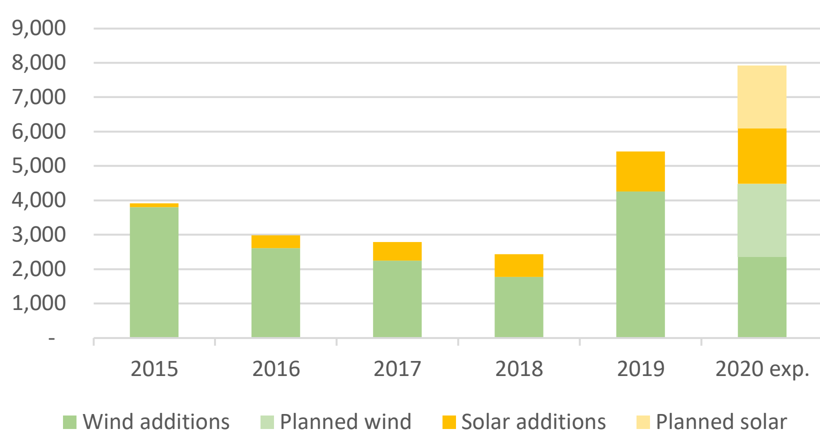
- Cohesive leadership across political and business community
- Extensive base of sophisticated decision-makers for energy-focused capital markets
- Global-scale energy players with large Houston presence pivoting to green investment to address climate-related risks to existing business operations
- Concentration of major renewable energy developers and owners
- Headquarters to many large retail power companies
- Highly skilled and diverse energy workforce
- World-class brown hydrogen infrastructure

TEXAS RENEWABLE GROWTH SUPPORTS PATHWAY TO NET ZERO GRID

2011-2019 renewable penetration vs CO2 intensity



2015-2020 (expected) ERCOT renewable additions, MW



To date, Texas has enjoyed robust renewable growth which has resulted in declining CO2 intensity

- Texas leads the nation in wind installations, with 27,219 MW installed in the ERCOT market at year end 2019, and another 7,910 MW expected to be in service by year-end 2020
- In less than a decade, the fraction of energy supplied by renewables has more than doubled
- The growth in renewables and a dramatic reduction in coal generation has resulted in ERCOT CO2 intensity declining 30% from 1,206 lb/MWh in 2010 to 850 lb/MWh in 2019

Texas pathway to sufficient renewables for a net zero grid by 2050

- As a result of numerous factors, including declining installation costs, improved conversion efficiencies, federal tax incentives, and corporate renewable energy purchases, renewable resources are expected to dominate ERCOT supply additions for the foreseeable future
- The vast scale of the potential ERCOT renewable resource base is demonstrated by examination of the ERCOT interconnection queue, listing wind development projects totaling 23,427 MW and solar projects of 59,205 MW
- By 2050 renewable capacity of 200 to 250 GW, along with the exiting carbon-free nuclear capacity and a requisite level of energy storage, could meet nearly all ERCOT demand on an hourly basis
- Achieving this level of renewable capacity equates to additions of 5,500 to 7,000 MW/year – in-line with 2020 expected renewable additions of 7,910 MW

Source: ERCOT GIS reports 2010-2020; US EIA; ERCOT Generation by Fuel Type Reports 2010-2019

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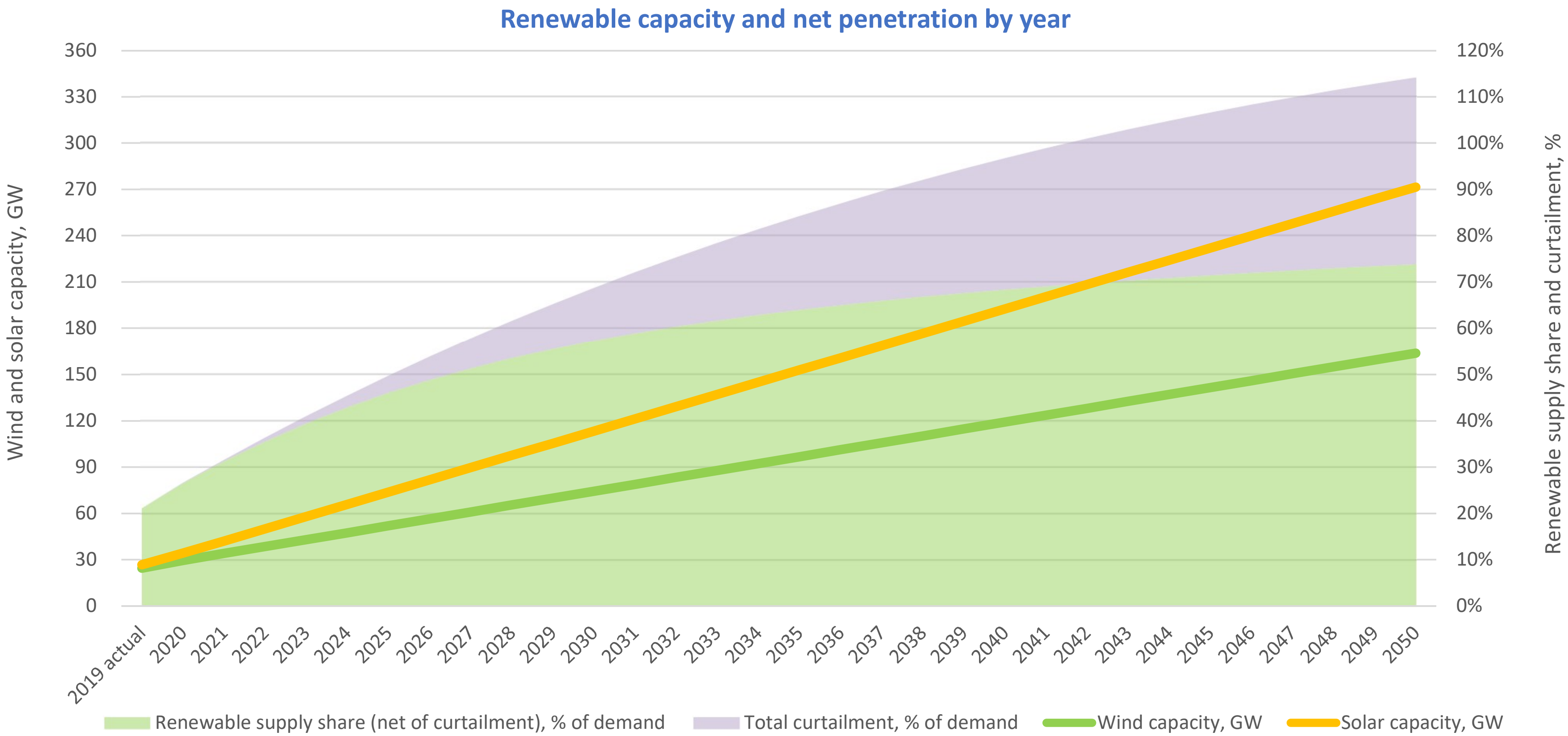
WITHOUT STORAGE, BENEFITS FROM RENEWABLE ADDITIONS PLATEAU

- The chart below shows the impact of increasing renewable capacity (absent energy storage) on renewable penetration and curtailment
- This chart assumes that renewable capacity is added every year from 2021 to 2050 at the 2020 expected rate (4,479 MW wind and 3,431 MW solar per year)
- Renewable supply share increases quickly in the early years, but realizes diminishing returns as renewable capacity continues to grow
- Investors are not likely to find returns from renewable projects attractive at levels of curtailment beyond 15 to 20% - the Production Tax Credit of~$25/MWh for wind is lost when curtailment occurs



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THREE KEY CHALLENGES ON THE PATHWAY TO NET ZERO GRID

Challenge 1: Renewable production is intermittent, and varies across hours of the day, months of the year, and across years, creating uncertainty of supply

- The variation in wind and solar production is evident in the chart on the right

Challenge 2: Renewable production patterns do not align well with ERCOT load (particularly with regard to West Texas wind), creating periods of under/over supply

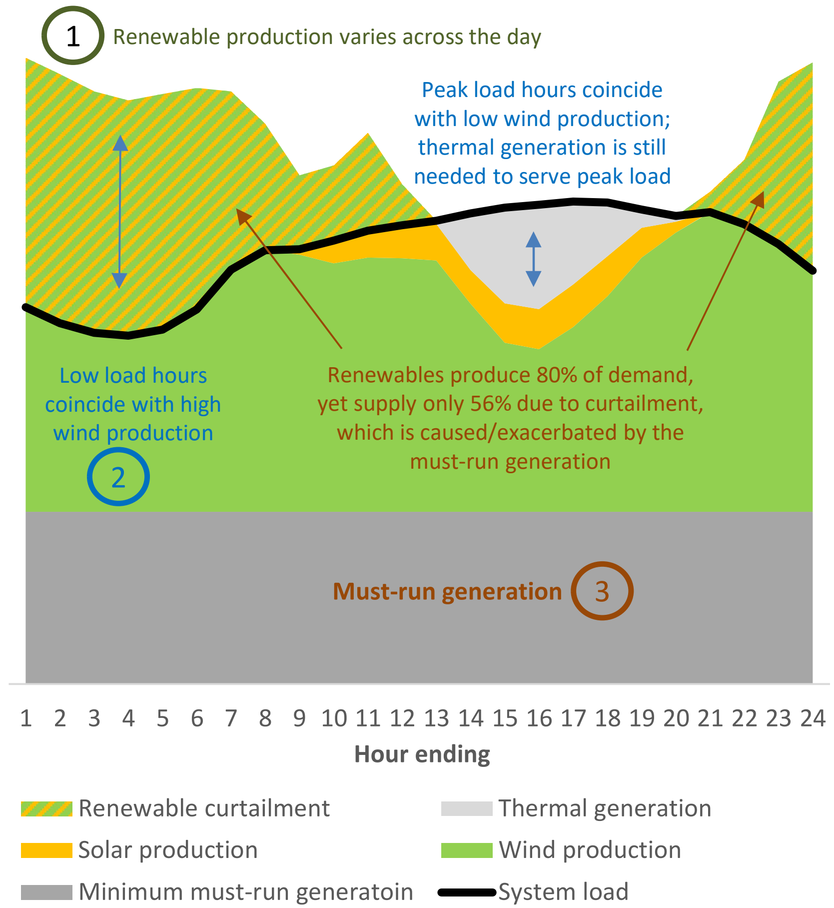
- Current mix of renewable production is lowest in the highest load hours, and highest when load is low
- While renewables can materially contribute to meeting demand during morning and evening hours, thermal generation is needed to serve load during peak hours

Challenge 3: Renewable production displaced by must-run generation during low-demand hours

- Must-run capacity includes nuclear units, cogeneration units, minimum output from online coal units, and units online to provide Ancillary Services
- Must-run units are price-taking – they will offer energy at very low/negative prices, at times displacing wind and solar generation in hours when high renewable output coincides with low demand
- Future challenge is mainly cogen must-run – nuclear is carbon-free, coal is likely to be retired, and new energy storage can provide Ancillary Services with minimal associated must-run energy

Illustrative diurnal load and production on a Spring day

This chart reflects the diurnal load and renewable production patterns on March 29, 2019 – renewables have been scaled up to produce 80% of total energy demand on this day



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PATHWAYS TOWARD NET ZERO GRID – STUDY APPROACH/METHODOLOGY

Intent of study

- Provide an understanding of the implications of very high renewable penetration and the role storage can play in enabling reliable, economic operation of a decarbonized grid

Study approach & scope

- Determine a suitable mix of wind and solar additions that minimizes over-supply/curtailment at high penetration levels
- Test supply-side solutions for relieving renewable over-supply, reducing CO2 intensity, and provided necessary firm back-up for renewable under-supply
    - Lithium-ion batteries
    - Compressed air energy storage (CAES)
    - Green hydrogen conversion for existing cogeneration (cogen) plants, existing, combined-cycle gas turbine (CCGT) plants, and CAES

Not in study scope

- Demand-side solutions or adjustments included in evaluation
- Increased electrification (beyond vehicles) or end-use efficiency improvements
- Improvements in renewable/storage performance or costs
- Other storage technologies that could become available over the study period were not evaluated
- Opportunity to push green hydrogen to markets other than power
- Economic impact of additional transmission needed to support high renewable penetration

Hourly market modeling methodology

- Start with actual 2019 hourly load, wind production, solar production, and prices for energy – grow hourly load, wind, and solar production to match future expectations
- Calculate hourly renewable over/under-supply and dispatch storage
- For each hour, use change in "net load" (system load less renewable production) to adjust the market heat rate (dt/MWh) up or down – net load represent the residual demand served by dispatchable generation and energy storage
- Energy price and spark spread found by multiplying adjusted heat rate by forward natural gas price in each hour
- ORDC & RTORDPA price adders calculated for each hour

Key inputs & assumptions

- Energy demand growth = 1.7%/year
- 2050 electric vehicle demand of 3.1 MM MWh
- Carbon price = $24-40/metric ton
- Retirement of today's coal capacity of 14 GW prior to 2050
- Gas-fired generation added as needed to maintain min. reserves
- Must-run capacity for Ancillary Services displaced by energy storage
- ERCOT congestion unchanged

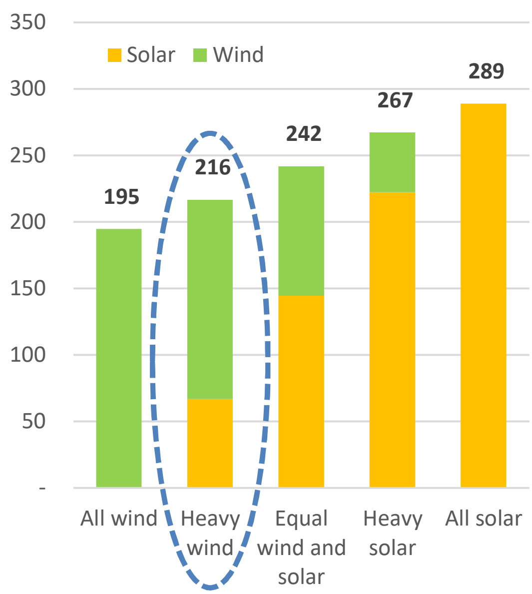
Output

- Hourly volumetric balance between renewable production and system demand accounting for must-run nuclear and cogen
- Hourly energy storage and hydrogen electrolyzer dispatch to meet balancing needs, as well as hourly storage inventory
- CO2 emissions from must-run and back-up generation
- Estimates of capital investment based on today's technology costs

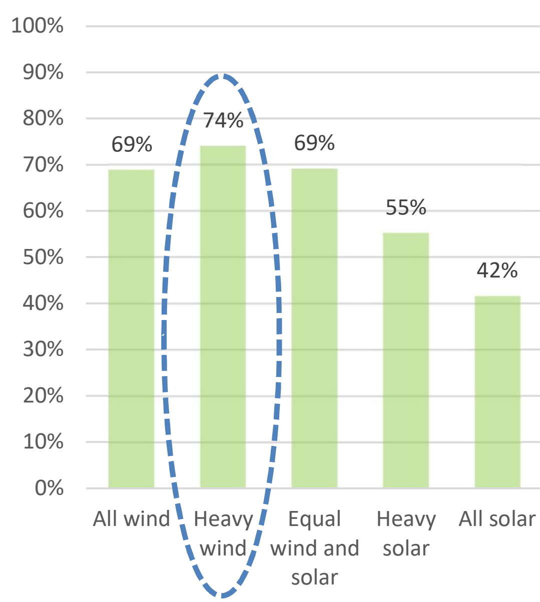
CURTAILMENT AND RENEWABLE PENETRATION VARY WITH MIX OF WIND AND SOLAR, BUT MIX CANNOT ELIMINATE OVER-SUPPLY

- To illustrate the challenge of matching energy supply to demand with high levels of renewable penetration, five scenarios were created:
  - 2019 ERCOT hourly load profile was adjusted to the year 2050, assuming a growth rate of 1.75% across all hours of the year
  - Renewable penetration scenarios under which unconstrained renewable (nameplate renewable resource capacity multiplied by 2019 hourly capacity factor) equaled the annual 2050 ERCOT demand not served by nuclear generation
- The figure on the left displays the nameplate wind and solar capacity for each of the five scenarios
- The middle figure displays the renewable supply share after curtailment; even the best apparent mix of ERCOT wind and solar results in substantial over-supply that would be "wasted" in the absence of energy storage (as shown in the figure on the right)
- Higher levels of solar additions result in particularly severe curtailment levels
- To evaluate the potential pathways to a net zero grid, the heavy wind scenario was chosen as the Base Case for further study

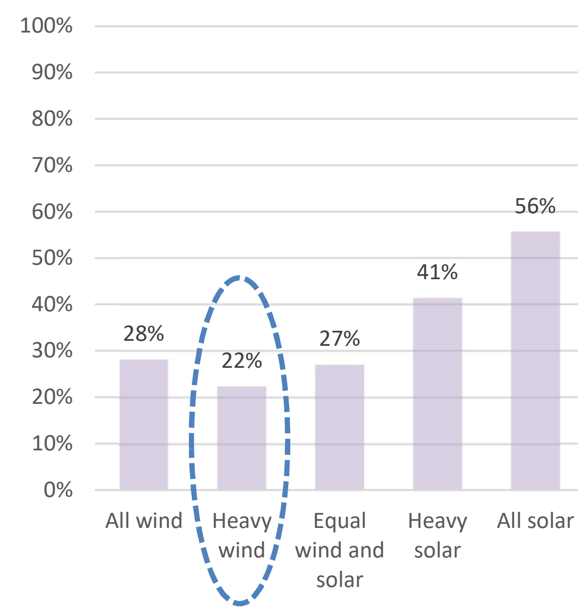
2050 renewable capacity, GW



Renewable supply after curtailment , % of load



Renewable over-supply, % of potential production



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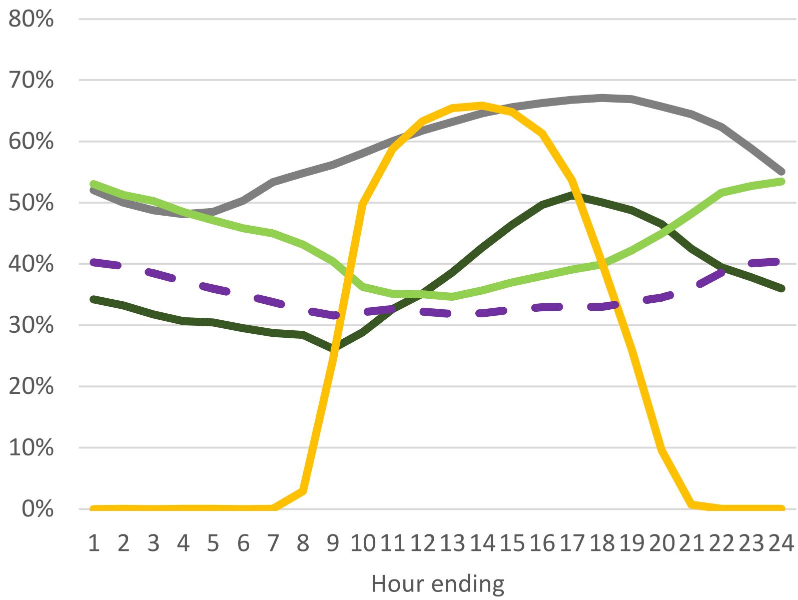
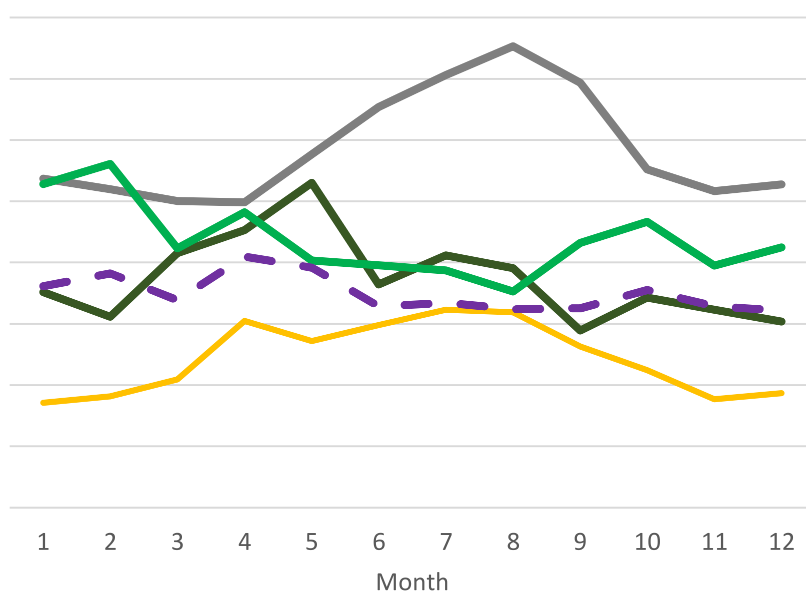
2050 BASE CASE RENEWABLE SCENARIO

- To develop an understanding of the implications of high renewable penetration without energy storage, a Base Case scenario incorporating sufficient renewable capacity to produce (assuming 2019 annual average average capacity factors) an amount of energy equal to the projected 2050 ERCOT annual demand (net of carbon-free nuclear generation) was created
  - Wind capacity is 149.8 GW, reflecting additions of 121.0 GW 2021-2050
  - Solar capacity is 66.7 GW, representing additions of 61.9 GW 2021-2050
- The lack of coincidence between the aggregate renewable output and system demand (less nuclear generation) inevitably leads to a high frequency of over or under-supply from the renewables

Diurnal capacity factor of load and renewable resources (2019 actual)



Monthly capacity factor of load and renewable resources (2019 actual)



ERCOT load — Coastal wind — Panhandle wind — ERCOT solar — 2019 renewable mix

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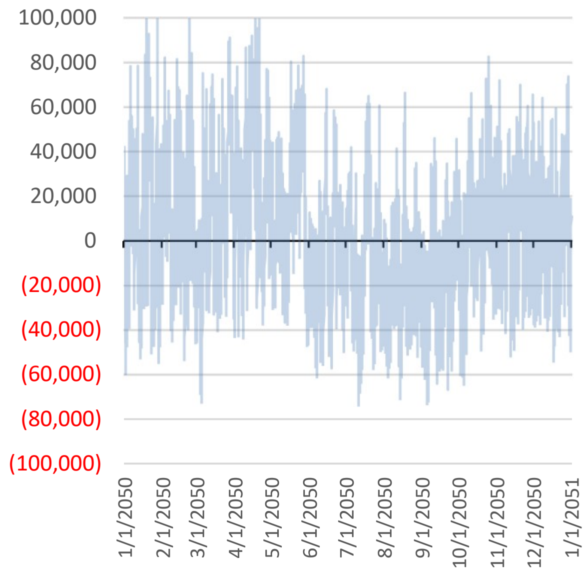
2050 BASE CASE* RENEWABLE OVER/UNDER-SUPPLY IN THE ABSENCE OF LARGE-SCALE ENERGY STORAGE SOLUTIONS

Absent energy storage, 22% of potential renewable production is curtailed

Daily/inter-day imbalances

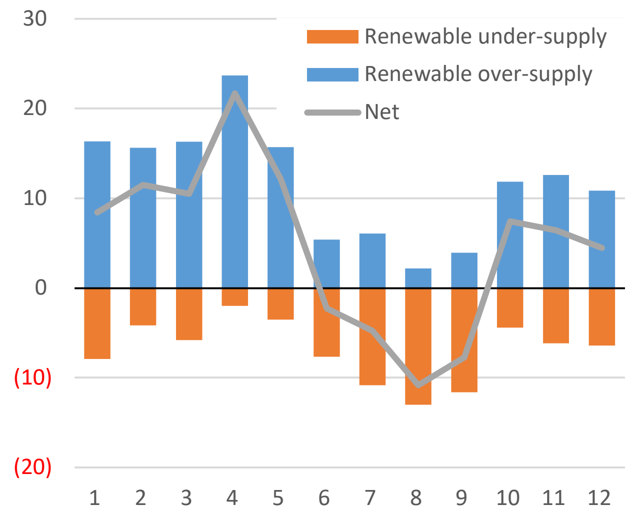
2050 (under)/ over-supply by hour, MW*



- Daily occurrences of significant over/under-supply
- Daily pattern is random

Seasonal imbalances

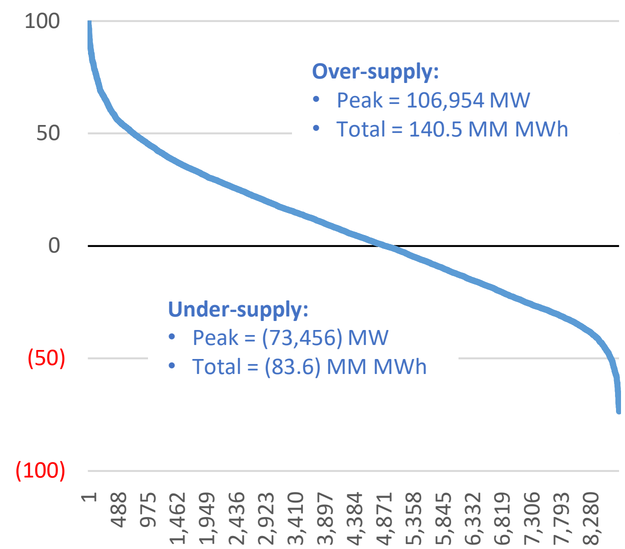
2050 renewable over and under-supply by month, MM MWh*



- High net over-supply in the spring season
- High net under-supply in the summer season

Size of over/under-supply

2050 ranked (under)/ over-supply by hour of the year, '000 MWh*



- Over-supply is larger than under-supply due to must-run capacity
- Approximately 10% of imbalances are greater than 50,000 MW

* Based on 2050 scenario with average load of 75,308 MW, 150 GW of wind capacity, 67 GW of solar capacity, 74% renewable penetration (prior to storage), and renewable curtailment equal to 22% of potential renewable production (before storage)

TODAY'S TECHNOLOGY SOLUTIONS FOR TEXAS RENEWABLE INTEGRATION

Although the storage technologies reflected in this analysis were limited to lithium-ion batteries, CAES, and green hydrogen conversion, other storage technologies can be expected to become available over the time frame of the study period

	How it works	Ratio of MWh-in to MWh-out	Storage duration	Today's installation cost*	Key advantages (+) & disadvantages (-)
Lithium-ion batteries	Power is absorbed by the battery and stored for later use via an electro-chemical process	0.85	1-4 hours	$1,137/kW @ 4 hours	(+) Bankable equipment from many reputable suppliers (-) Storage adequate for <10% of over-supply events
Compressed Air Energy Storage (CAES)	Electricity is used to compress air, which is then stored and later used to run a turbine generator	1.69	+48 hours	$1,295/kW @ 48 hours	(+) Bankable equipment from Siemens (+) Storage adequate for >50% of over-supply events (-) CAES uses a small amount of natural gas in the expansion process
CAES converted to green H2	Electrolysis uses electricity to separate water into hydrogen and oxygen; the hydrogen can be stored and later used as fuel in existing natural gas-fired turbines	0.63	Multi-day/ seasonal	H2 electrolysis = $1,000/kW H2 storage = $16.25/Bbl CCGT = $1,000/kW	(+) Better fuel efficiency than cogen/CCGT (+) Suited to co-location of H2 storage (-) Requires incr. renewable additions
Cogen converted to green H2		0.52			(+) Reduce must-run CO2 emitting supply (+) Utilize existing cogen capacity (-) Requires incr. renewable additions
NG generation converted to green H2		0.33			(+) Power industry standard technology (+) 45 GW existing CCGT fleet in ERCOT (-) Low ratio of MWH-in to MWh-out (-) requires large incr. renewable additions

* Lithium-ion installation costs based on Lazard Levelized Cost of Storage Report, Nov. 2019; 100 MW scale with $232/kW-hour lithium-ion module cost (storage media); CAES based on Apex ERCOT estimate; H2 electrolyzer based on estimate of utility-scale (Hydrogen Council, Path to Hydrogen Competitiveness, January, 2020); H2 cavern cost assumed to be ~16.25/Bbl

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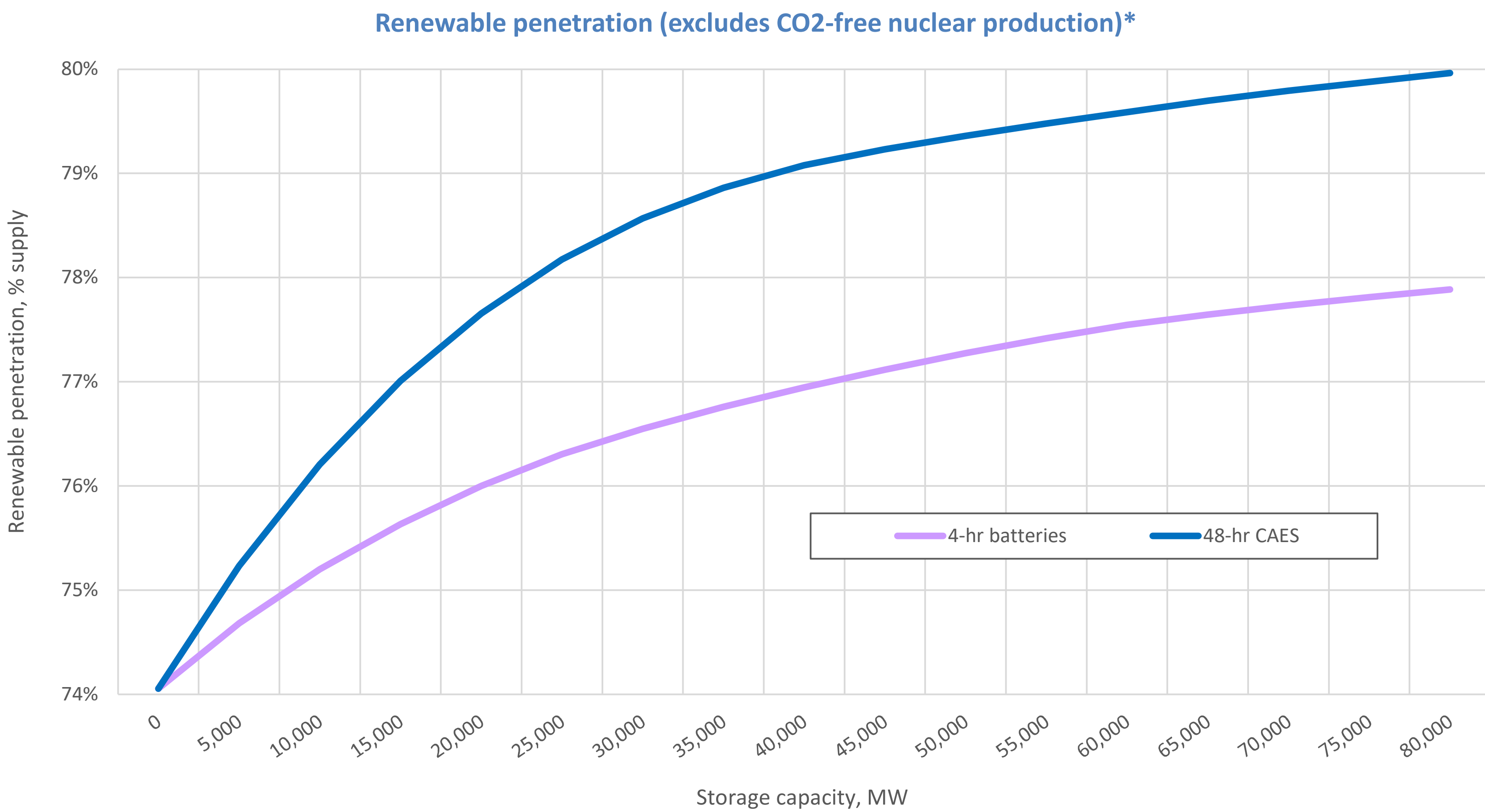
48-HOUR STORAGE REDUCES MORE CARBON, BUT ALL STORAGE REALIZES DIMINISHING BENEFITS AS CAPACITY GROWS

- CAES longer storage duration allows for more charging and greater utilization of renewable production
- Incremental benefits of CAES diminish at capacity additions greater than ~30,000 MW



* Based on 2050 scenario with average load of 75,308 MW, 150 GW of wind capacity, 67 GW of solar capacity, 74% renewable penetration (prior to storage), and renewable curtailment equal to 22% of potential renewable production (before storage)

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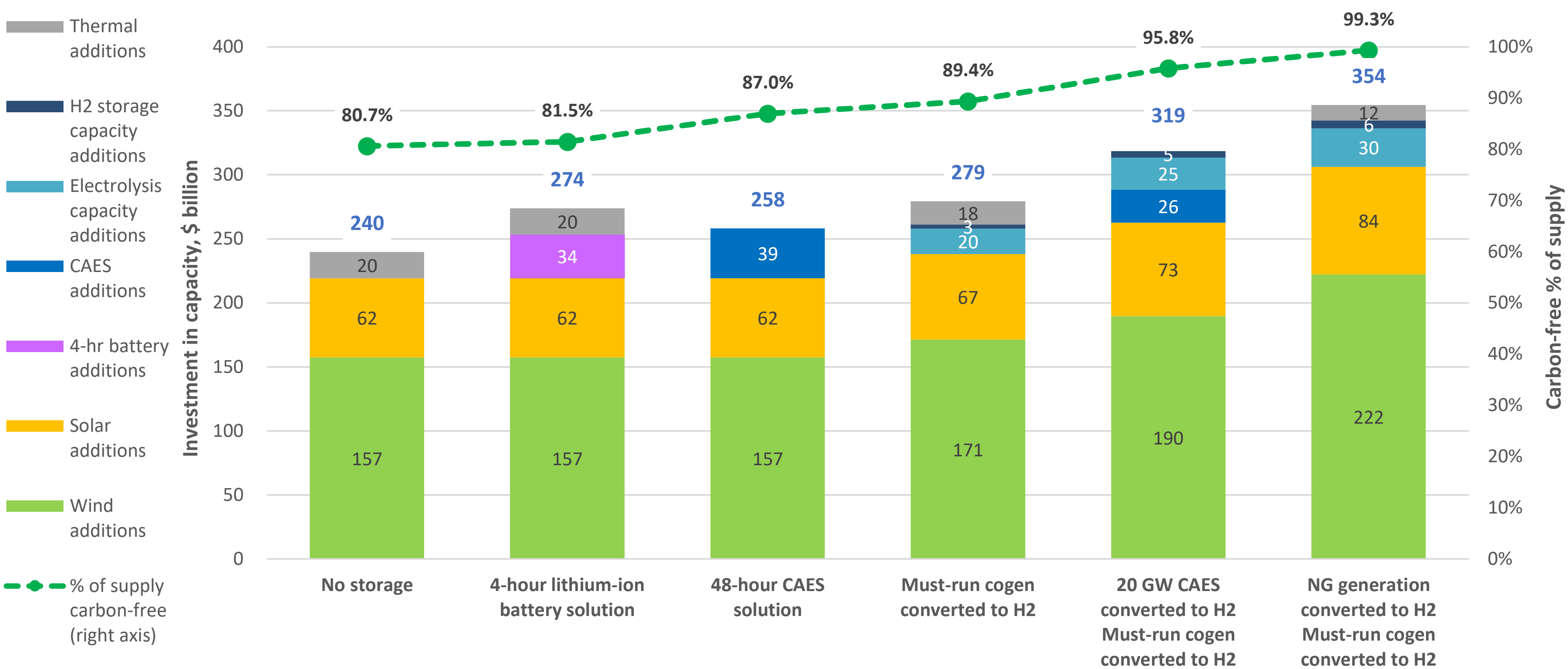
APPROACHING A NET ZERO GRID – FIVE STORAGE SCENARIOS

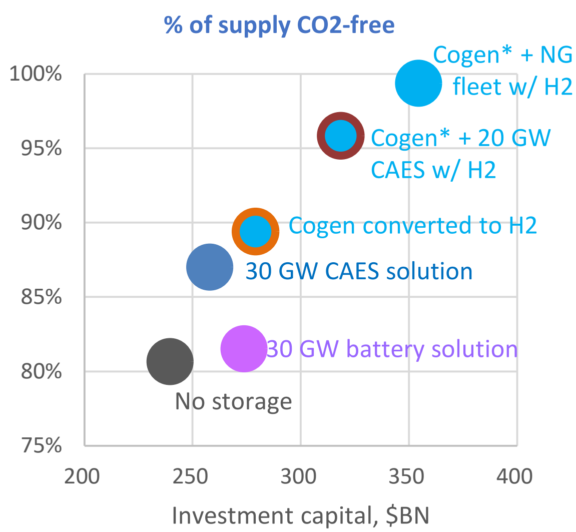
Investment in capacity additions 2021-2050, $BN



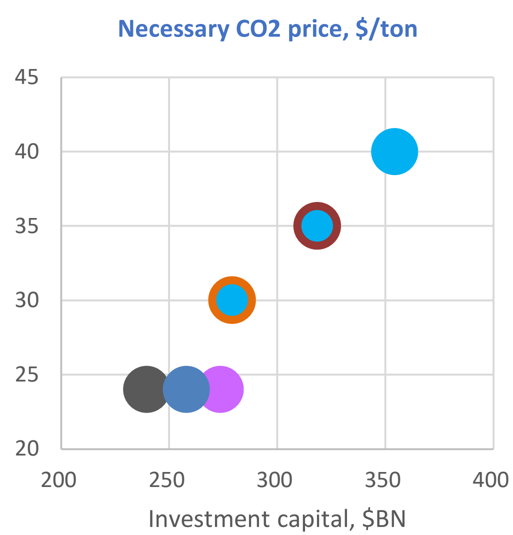
2021-2050 incremental additions, MW					(50% cogen retired)	(50% cogen retired)
Wind capacity, MW	121,048	121,048	121,048	131,779	145,839	170,917
Solar capacity, MW	61,895	61,895	61,895	66,670	72,926	84,085
Storage capacity, MW	0	30,000	30,000	0	20,000	0
H2 electrolysis capacity, MW	0	0	0	20,000	25,000	30,000
NG capacity, MW	20,432	20,432	0	18,032	0	11,932
H2 storage capacity, MMBbl*	0	0	0	200	316	384

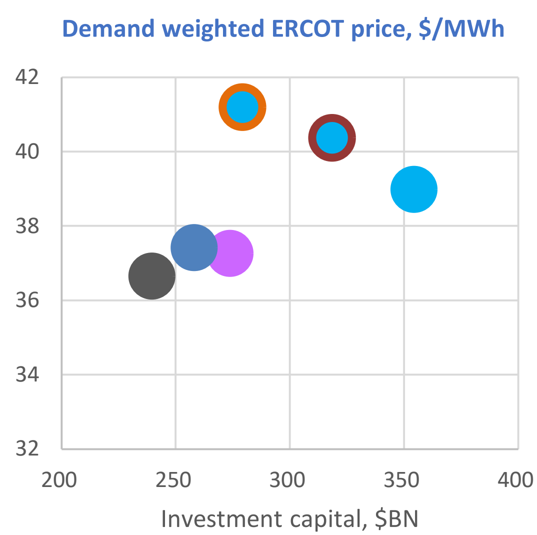
* Some portion of necessary hydrogen storage capacity may be repurposed natural gas storage capacity

SUMMARY FINDINGS - FIVE STORAGE SCENARIOS



- Renewables, absent energy storage, can support only ~80% CO_2-free supply before over-supply is greater than 20%, assuming a CO_2 price of $24/ton
- Long duration energy storage (CAES) can support closer to 90% CO_2-free supply before storage additions begin to suffer diminishing benefits
- Greater than 90% CO_2-free supply is possible with green H_2 conversion of cogen and existing NG-fired resources, but investment costs are materially higher due to the additional renewable capacity needed for green H_2 production, as well as H_2 electrolysis and storage capacity additions





- Green H_2 conversion requires a higher CO_2 price to maintain the returns for additional renewable investment
- Greater renewable capacity in the hydrogen scenarios results in more hours in which renewables are on the margin – carbon pricing will have no impact on clearing prices in these hours
- The higher CO_2 price needed to support H_2 conversion results in an increase in ERCOT wholesale pricing of $2 to 5/MWh or $1.3 to 3.3 billion/year

* Assumes 50% of cogen capacity retired

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ROADMAP TOWARD NET ZERO GRID BY 2050

2020-2025 | **2025-2040** | **2040-2050**

- **Continue annual wind and solar additions**
- **Maintain tax credits for wind and solar**
- **Accelerate expansion of ERCOT transmission capacity**
- **Growth in ESG investment appetite**

2020-2025

Support eligibility of standalone energy storage for federal Investment Tax Credits

Support implementation of a carbon tax/price

2025-2040

Add long duration storage to mitigate renewable over-supply

Begin using electrolysis to capture increasingly over-supplied/curtailed renewables

Convert existing salt dome infrastructure to H2 storage

Begin upgrading existing cogeneration to use H2 in the fuel mix

2040-2050

Convert existing gas-fired generation for H2 fuel to back up renewables

Continue upgrade of existing cogeneration to run on increasingly higher mixes of H2

Build new H2 storage capacity

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Why Houston Will Be the Capital of a Low Carbon Energy World: Circular Plastics Economy

Kamran R. Bhattacharya (BBA Finance)
William J. Nordt (BBA Supply Chain & MIS)
Thanks to: Jing Ping (MS Finance)
Faculty Mentor: Ramanan Krishnamoorti, Radha Radhakrishnan, and Alan Rossiter

October 8th, 2020

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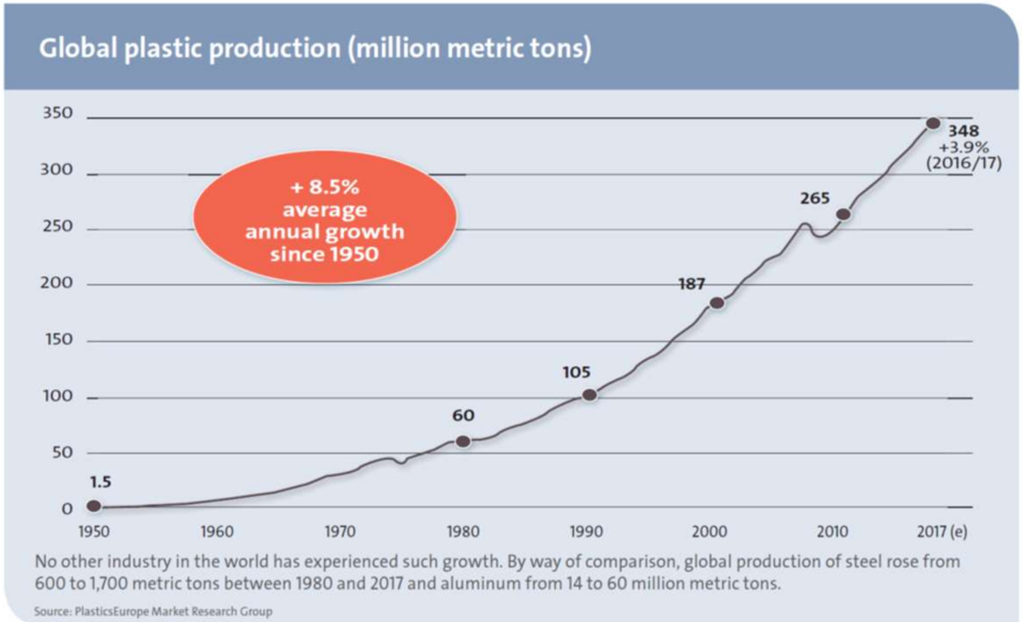
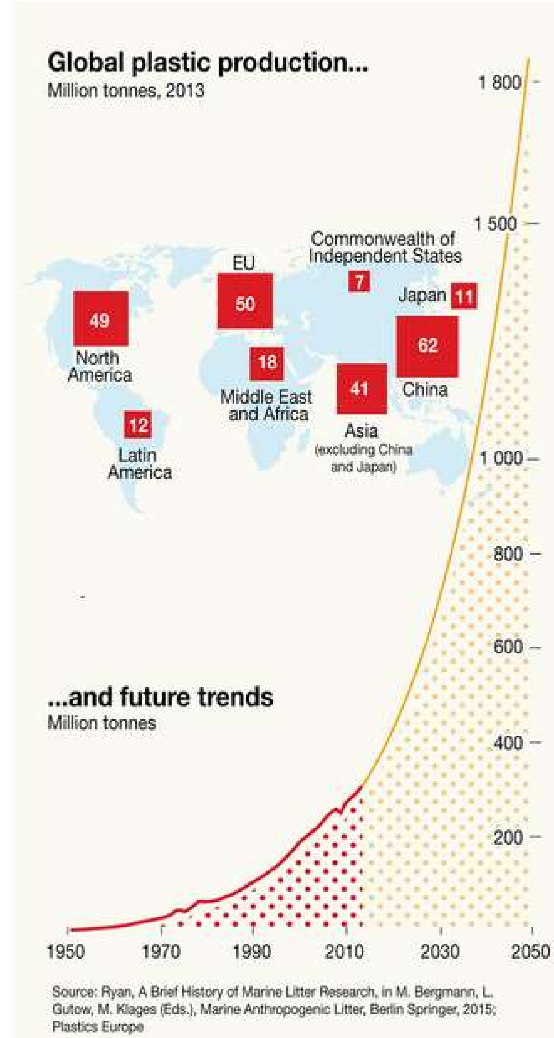
Global Plastic Production & Emissions Challenge





Global Annual Emissions from Plastic Lifecycle (in CO_2e)

2019	2030	2050
0.86 Gt	1.34 Gt	2.80 Gt

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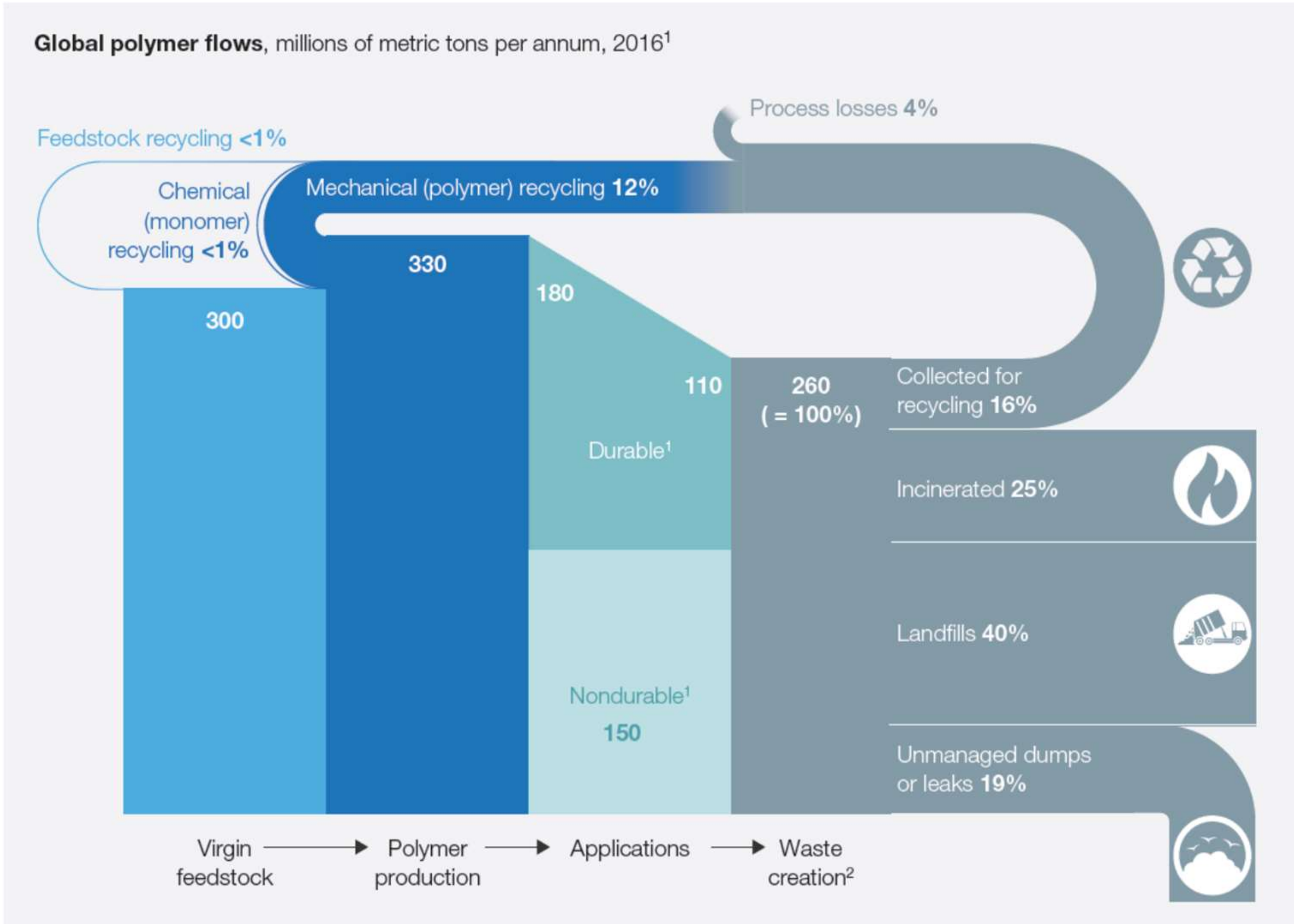
Houston & Gulf Coast: Leading Advanced Plastics Recycling

- Houston MSA Dominates the U.S. Production of Plastic Resins, including significant quantities for export
  - 49% of Country's Polypropylene Capacity
  - 40% of U.S. Polyethylene Capacity
  - 52% of Country's Poly(vinyl chloride) Capacity (TX+LA: >80% of U.S. Capacity)
- The plastic manufacturing industry supports 10,284 jobs over 231 establishments (Houston MSA)(in 2018)
- In 2015, the CO_2e emissions (cradle-to-resin) for plastic manufactured in Houston MSA ~ 30 Million Metric tons of CO_2e
- Houston also has some of the largest Waste Management and Plastic Recycling companies
- Large source of commercial and industrial waste with more secure supply-chain

Global Circular Plastics Economy

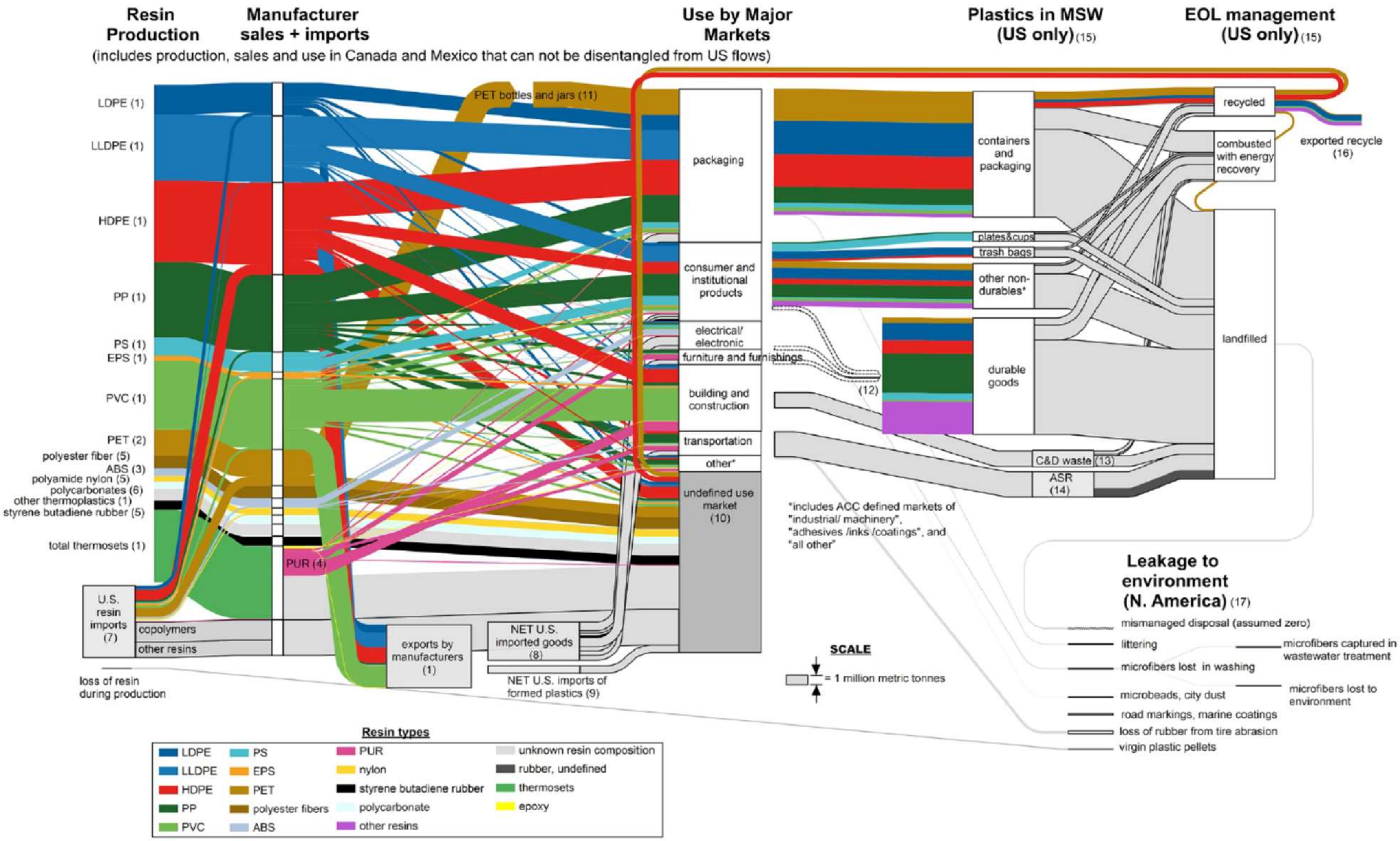


Durable application with lifetime > 1 year will end up in waste in later years

In U.S. Minimal Leakage of Plastic Waste to Marine Environment

McKinsey, 2018, How Plastics-Waste Recycling Could Transform the Chemical Industry

U.S. Circular Plastics Economy



Heller, 2020 Environ. Res. Lett.

Objectives and Findings

- Scope of Potential Regional Investments
  - Chemical recycling/regeneration of plastics
    - New technology to reduce polymers to monomers
    - Integration with existing downstream petrochemical product processing plants
- Key Investment/Technology Challenges/Assumptions
  - Chemical remanufacturing technology
  - Investment required in collection of recyclable materials
- Focus of Our Work:
  - Improve Single-Use Plastics Recycling to 100% by 2030
  - Reuse or Recycle – 100% of <u>all</u> plastic waste by 2050
  - Decrease GHG impact by 90% by 2050
- Exploiting the unique advantage of Houston MSA / Gulf Coast Ecosystem
  - Polymer Manufacturing Infrastructure and Workforce
  - Large Fraction of Commercial and Industrial Waste
  - Integration of Renewable Energy (50% Decrease in GHG)
- Advanced Recycling Opportunities
- Alternates to Single-Stream Residential Recycling

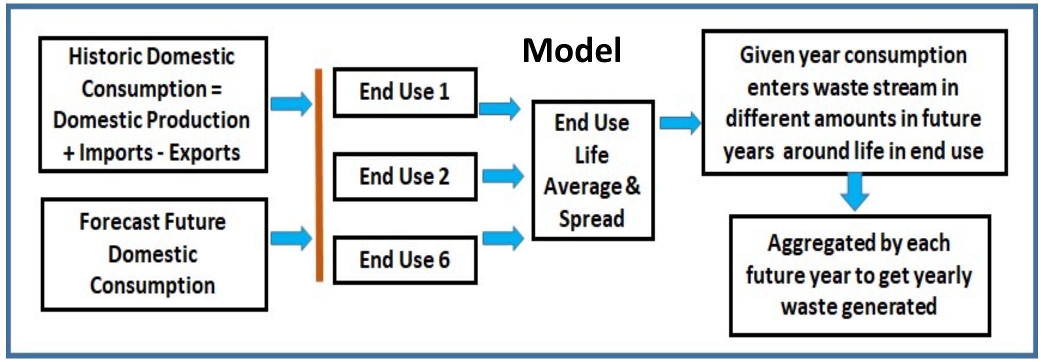
Plastic Waste Generation Assessment Methodology

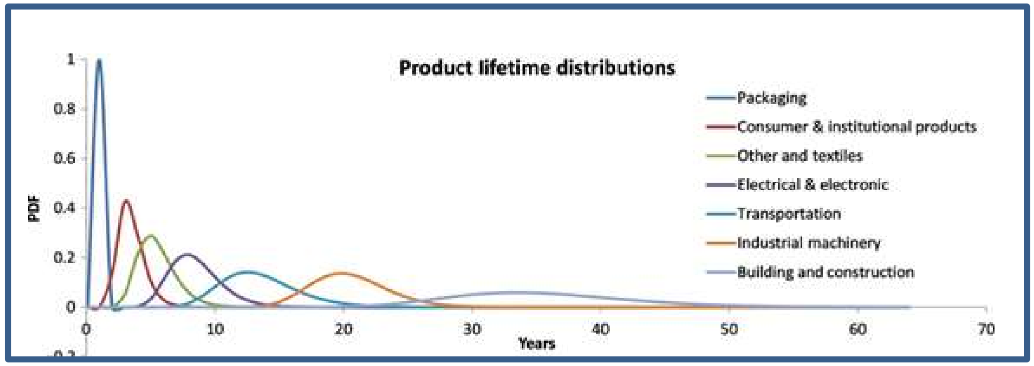
Plastics Considered

- HDPE
- LDPE,LLDPE
- PVC
- PP
- PS
- PET

Key Model Assumptions

- Product lifetime in end uses
- Plastic consumed ends up as waste – no leakages
- Past consumption pattern continue into the future
- Potential future policies impacting plastic consumption are not considered.
- 2017 National Population Projections (Main Series) and US GDP growth of 2.4% per annum were used to forecast future plastic consumption





End Use	Mean (in yrs)	Std. Dev. (in yrs)
Packaging	0.5	0.1
Transportation	13	3
Building and Construction	35	7
Electrical / Electronic	8	2
Consumer & Institutional	3	1
Industrial Machinery	20	3
Textile & Other	5	1.5

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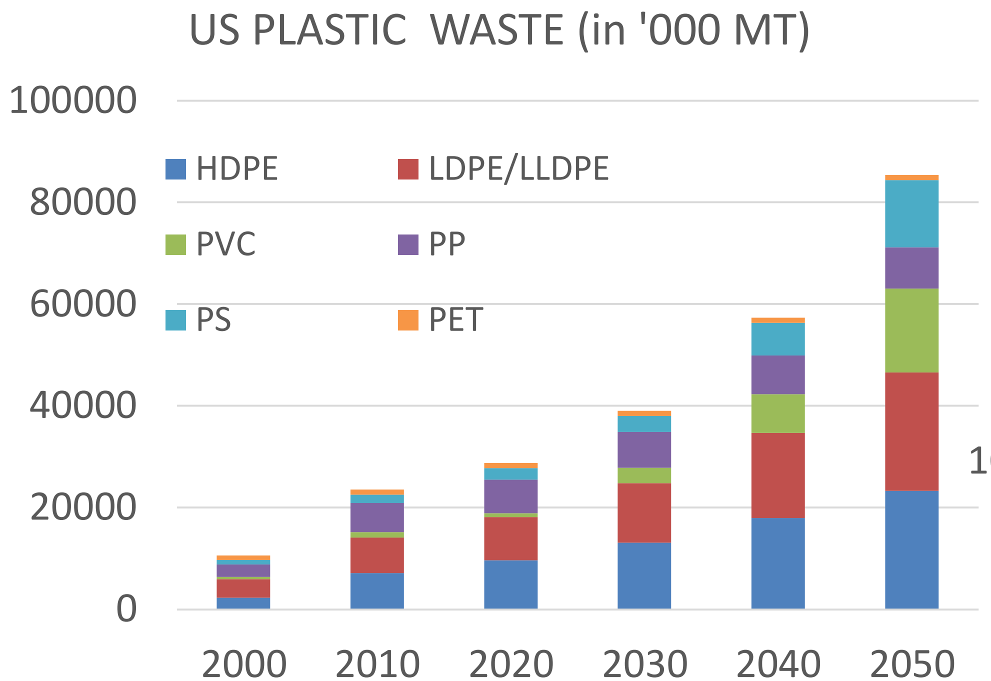
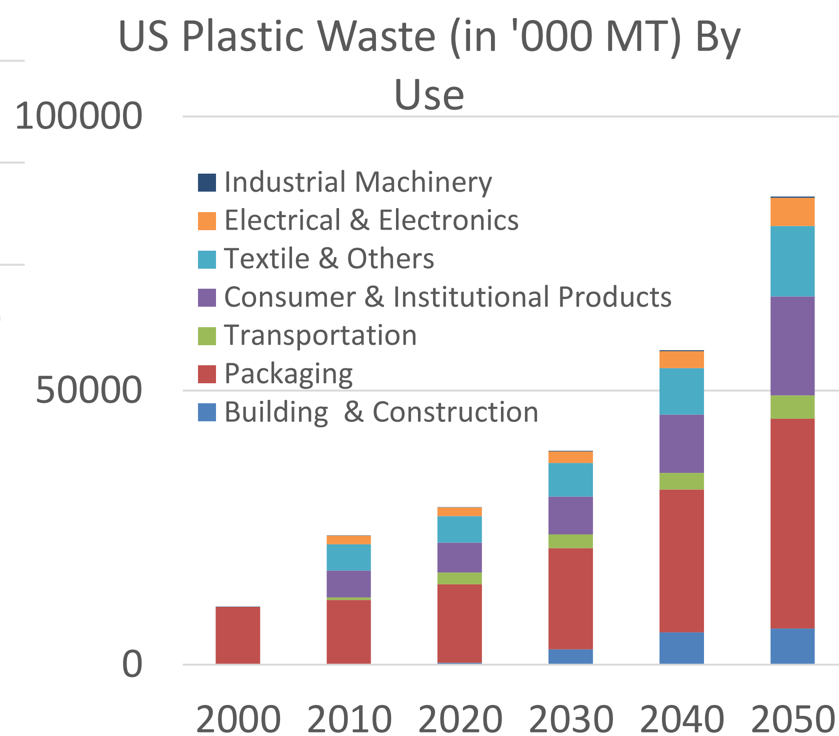
Cradle – to – Resin GHG Emissions in US

Resin	Mass Emissions Factor (g CO2e/ g plastic)	CO2e in 2020 (million metric tons)	CO2e in 2030 (million metric tons)	CO2e in 2050 (million metric tons)
High Density Polyethylene (HDPE)	1.5	14.1	17.5	26.8
Low Density Polyethylene (LDPE)	1.8	6.2	7.8	11.1
Linear Low Density Polyethylene (LLDPE)	1.5	11.3	13.5	19.8
Polypropylene (PP)	1.5	13.2	15.8	26.4
Polyvinyl Chloride (PVC)	2.2	15.5	19.8	28.4
Polyethylene Terephthalate (PET)	2.4	7.5	9.0	12.1
Polystyrene	3.1	6.8	8.3	10.5
Total		**~ 75**	**~ 90**	**~ 154**

U.S. Plastic Waste Generation





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Houston MSA Plastic Waste Generation

GHG Impact

Year	CO_2e in million metric tons
2020	75
2030	90
2050	154

Address 100% Single-Use Plastics
Increasing All Plastic Recycling to >40% by **2030**

- Barriers: Collection, Cleaning, Sorting, Delamination, Elimination of Inks, Additives and Fillers
- Opportunity:
  - Distributed Collection (now Collection at Aggregators)
  - Multi-bin Collection or Digital Tagging
  - Chemical / Solvolysis: Delamination & Deinking
  - Advanced Recycling Methods
- Advanced Recycling in Houston MSA by 2030
  - 100 Advanced Recycling Facilities each handling 25,000 tons per year
  - Investment of $3.5 Billion
  - Create 15,000 New Jobs & Annual Payroll of $0.5 Billion
  - Save over 5,000 Jobs Directly
  - Reduce GHG Emissions 10 Million Metric Tons per year
- Action Items:
  - Improved collection and sorting: Replicate Extended Producer Responsibility (EPR)
  - Education & Behavioral Changes
  - Collection and Recycling of Industrial and Commercial Waste

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Recycling 100% Plastics by **2050**

- Barriers: Collection, Cleaning, Sorting, Energy Demand
- Opportunity:
  - Multi-bin Sorting
  - Improved Sorting and Cleaning at MRFs
  - Separation of Recycle Code 3-7 (PVC, LDPE, PP, PS, Other) Wastes
  - Integration of Renewables with Plastics Re-manufacturing
- Advanced Recycling in Houston MSA by 2050
  - 300 Advanced Recycling Facilities each handling 25,000 tons per year
  - Investment of $15 Billion
  - Create 50,000 New Jobs & Annual Payroll of $1.8 Billion
  - Save over 10,000 Jobs Directly
  - Reduce GHG Emissions 135 Million Metric Tons per year
- Action Items:
  - Incentives for Separation and Recycling of 3-7 Codes: High CO_2e Impact: Carbon Tax
  - Integration of Renewables for Plastic Re-manufacturing: PTC
  - Expanding MRFs

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Waste Management
Avangard
FCC
City of Houston
Houston-Galveston Area Council

Thank you!