AIChE® 13th SOUTHWEST PROCESS TECHNOLOGY CONFERENCE

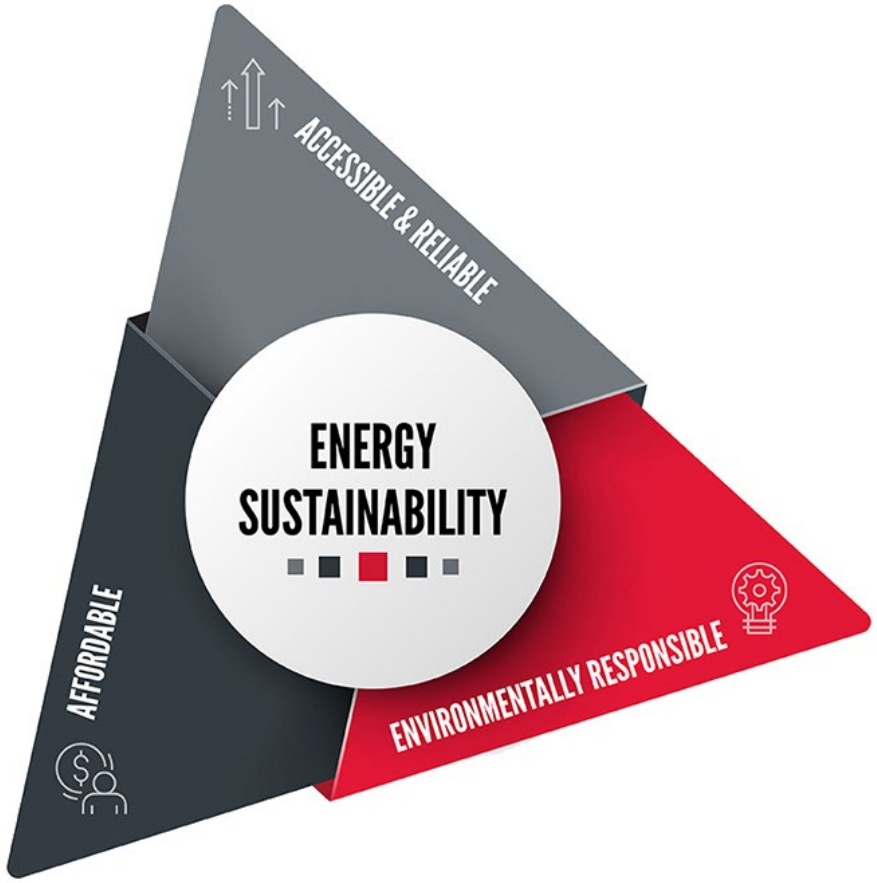
September 30 - October 1, 2021

Sugar Land Marriott Town Square, Texas

Houston as the Low Carbon Capital of the World

Charles McConnell, University of Houston

What is Real Sustainability ??



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What is the Real Mission and Objective?

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- More renewables

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- Battery storage

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- Technology Transformation

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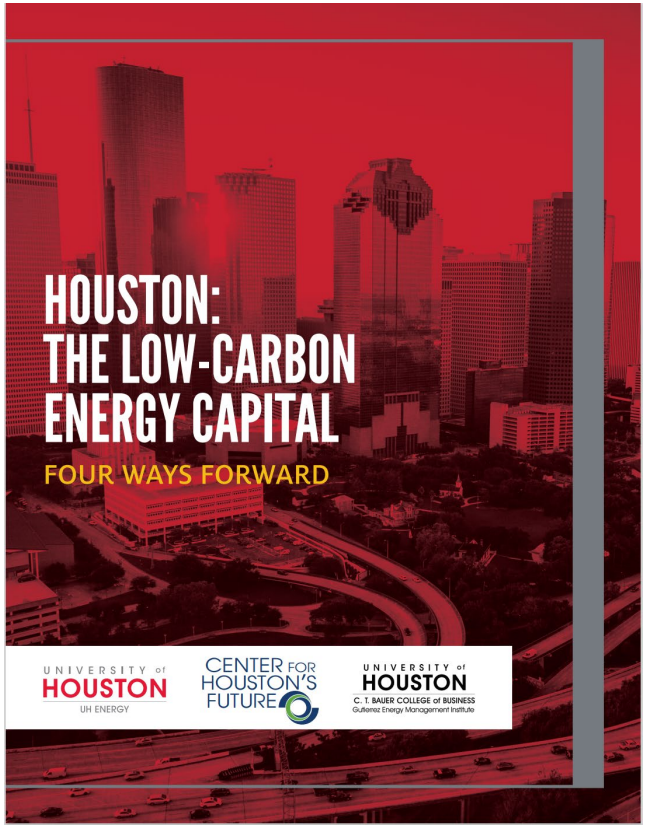
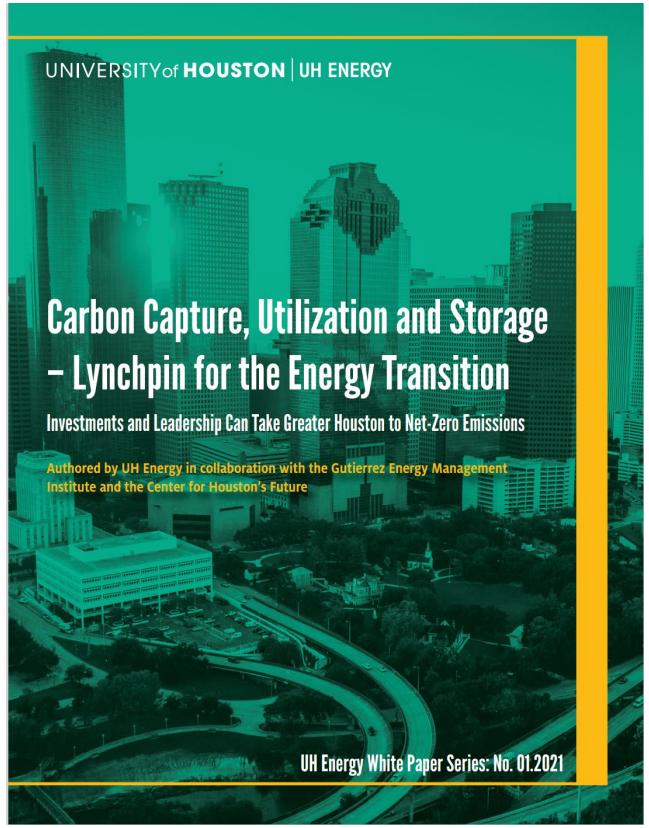
ALL OF THESE ARE TACTICS –The Mission is Emissions Reduction

Source Information



https://uh.edu/uh-energy/energy-symposium-series/low-carbon-energy-capital/content/uh-energy-houston-low-carbon-energy-capital-four-ways-forward.pdf



https://uh.edu/uh-energy/research/white-papers/ccus-entry-form

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Low Carbon Energy Capital Project

Carbon, Capture, Use, and Storage (CCUS)

Team – Initiative 1

Makpal Sariyeva, Paty Hernandez, Brad Peurifoy

Faculty Mentor: Charles McConnell

October 9th, 2020

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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.

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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.

Key Challenges to Address in Project

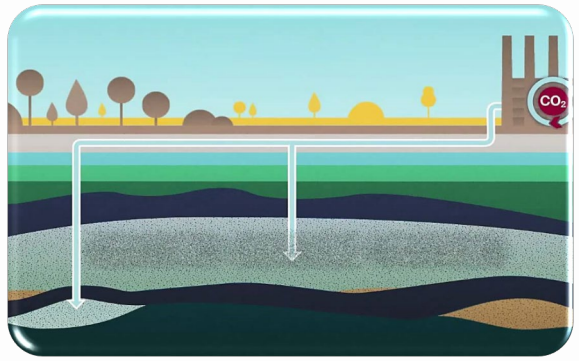
Carbon Capture

- 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

Key Takeaways

- **Phase I (present to 2030):**
  - **Focus on Low cost strategic CO2 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

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- **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

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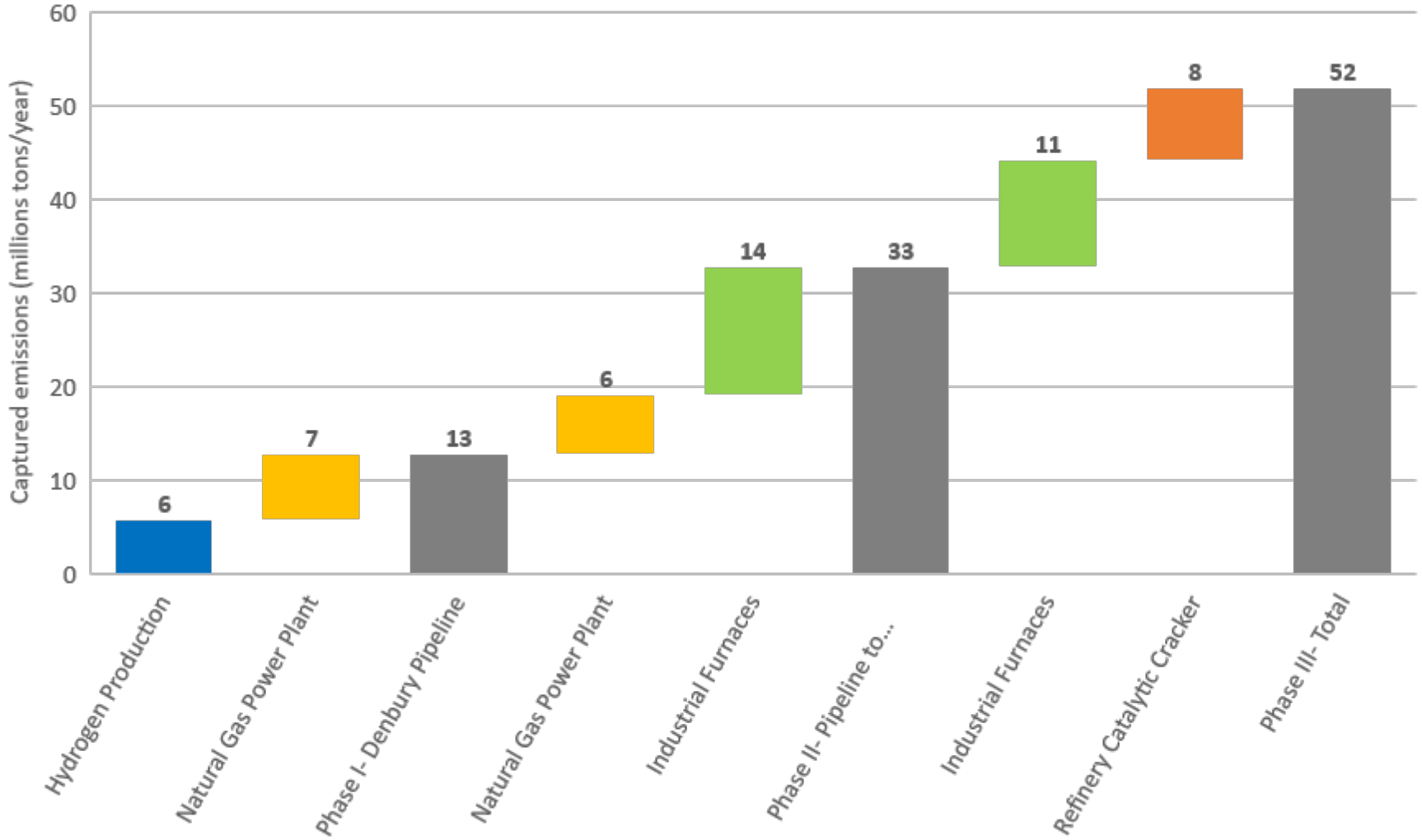
- **Phase III (2050):**
  - **Expand capture to include: 11.4 million** tons/yr from Industrial Furnaces
    7.8 million tons/yr from Refinery Catalytic Cracker
  - **Build pipeline to the Permian:** 20 million tons/yr available capacity at US$1 billion cost (500 miles X US$2 million/mile)
  - **Permian available geologic storage:** 4.8 billion tons of EOR and 1 trillion tons of saline

Phase I: Activation – Gulf Coast



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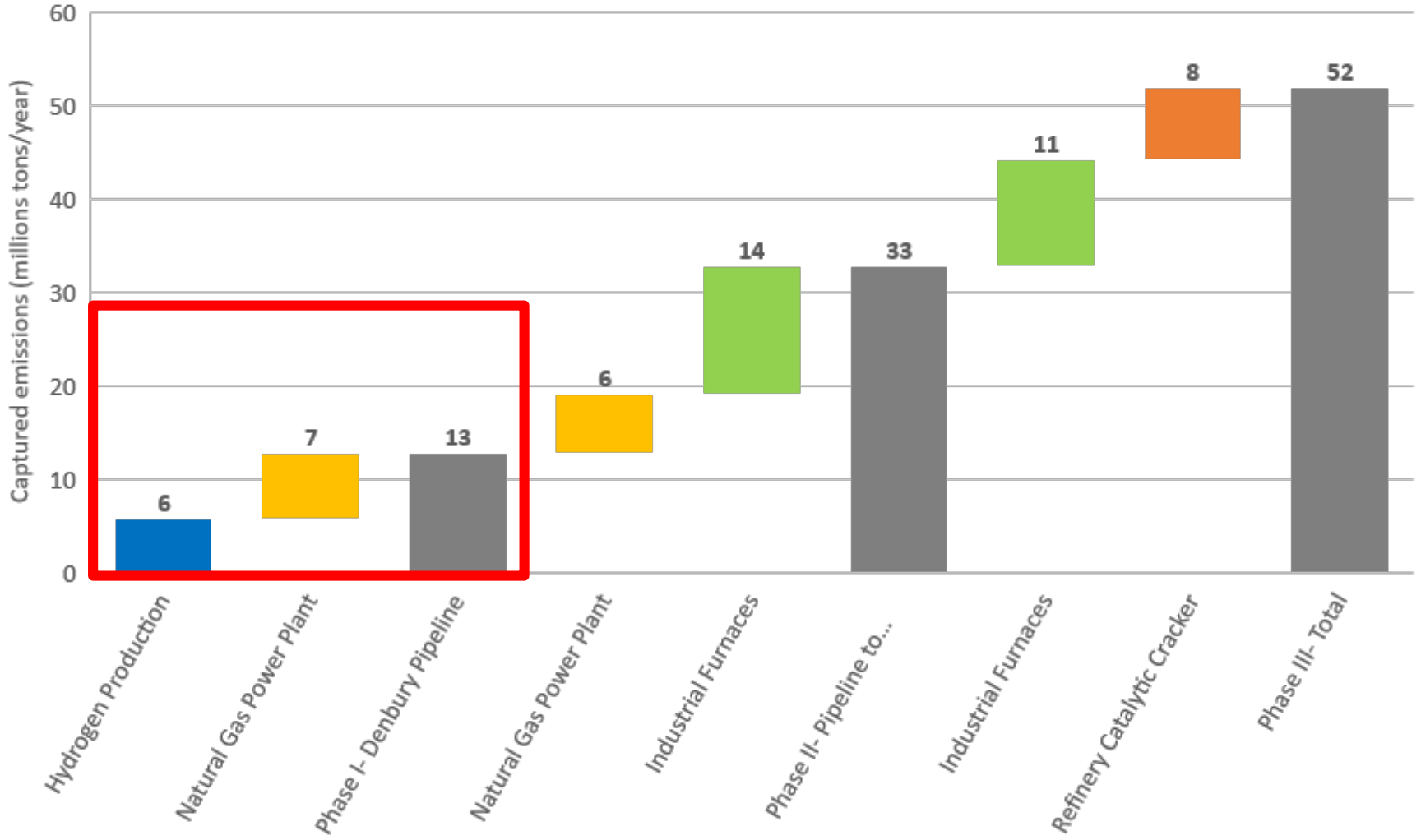


Phase I: Activation (2030)

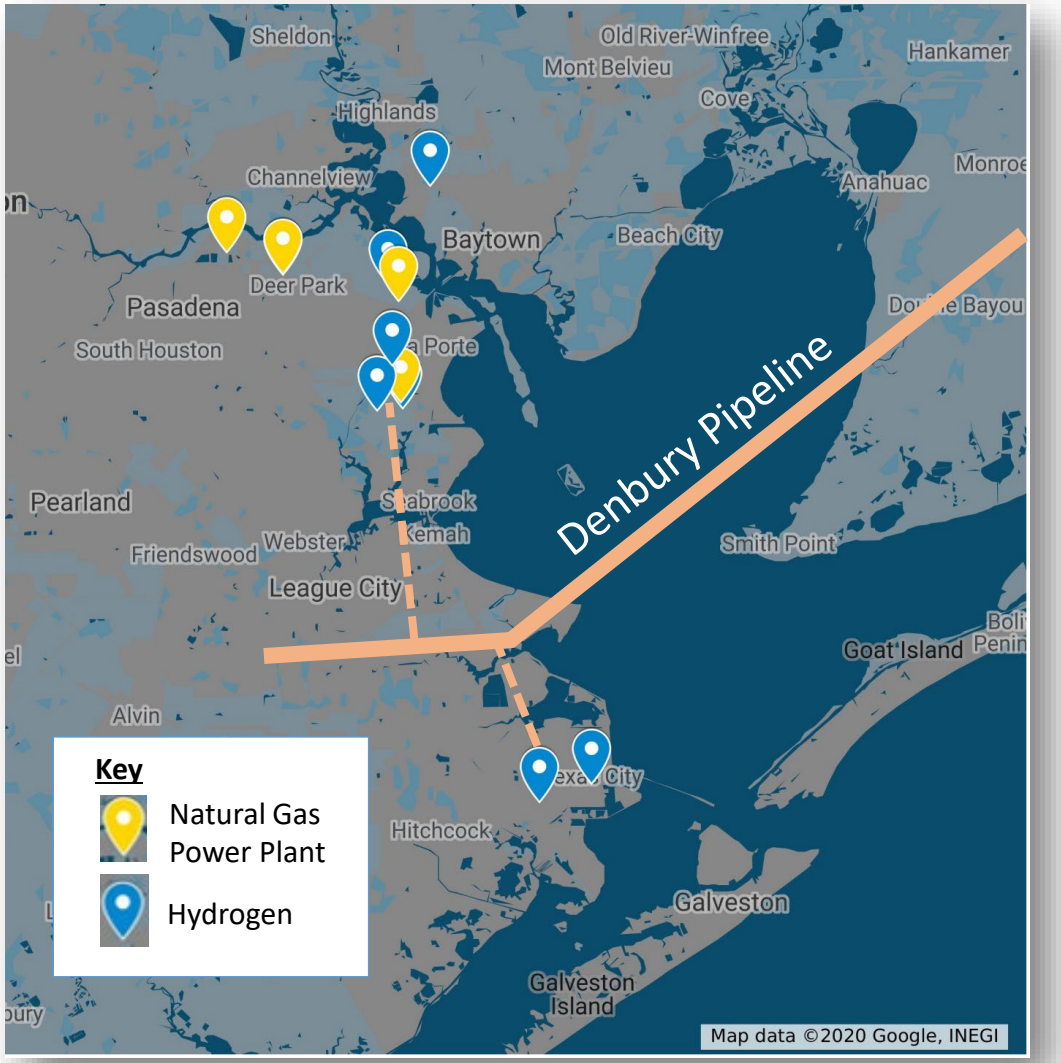
Capture

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**.

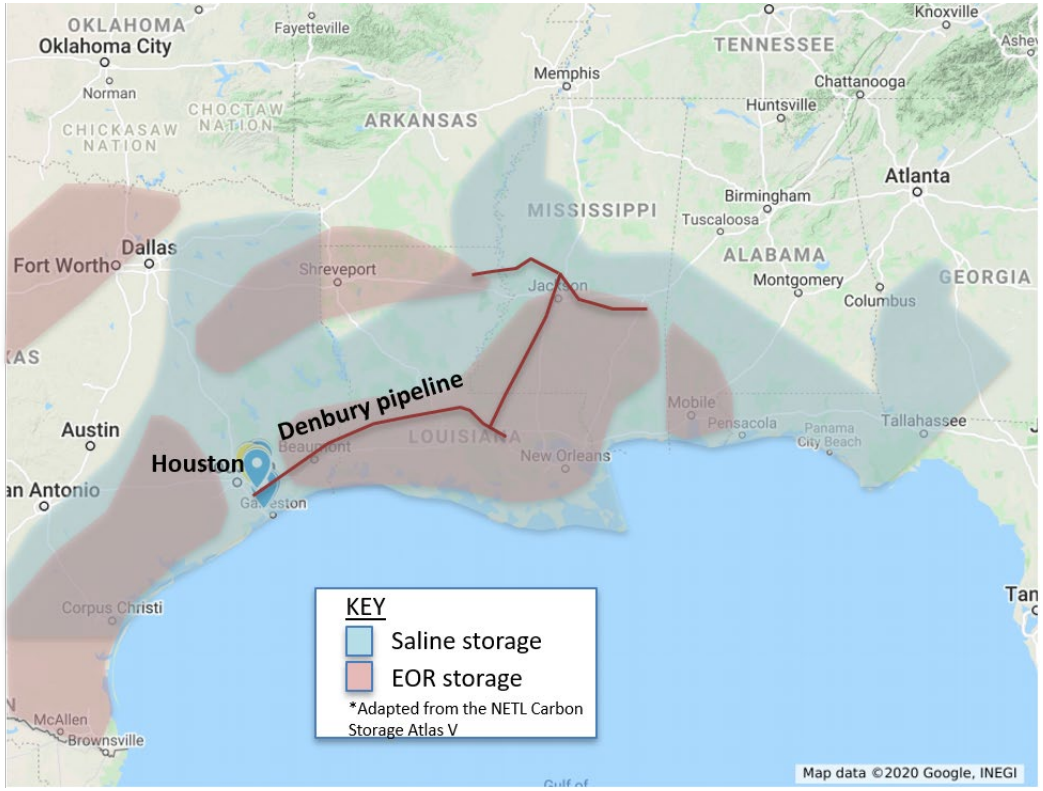


Phase I: Activation (2030)

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	$			

	Oil Price (inflated 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
Revenue	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
Revenue	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
Revenue	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
Capex	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
Capex	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
Opex	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	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
Opex	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
Opex	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	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
Opex	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
Opex	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	$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%																

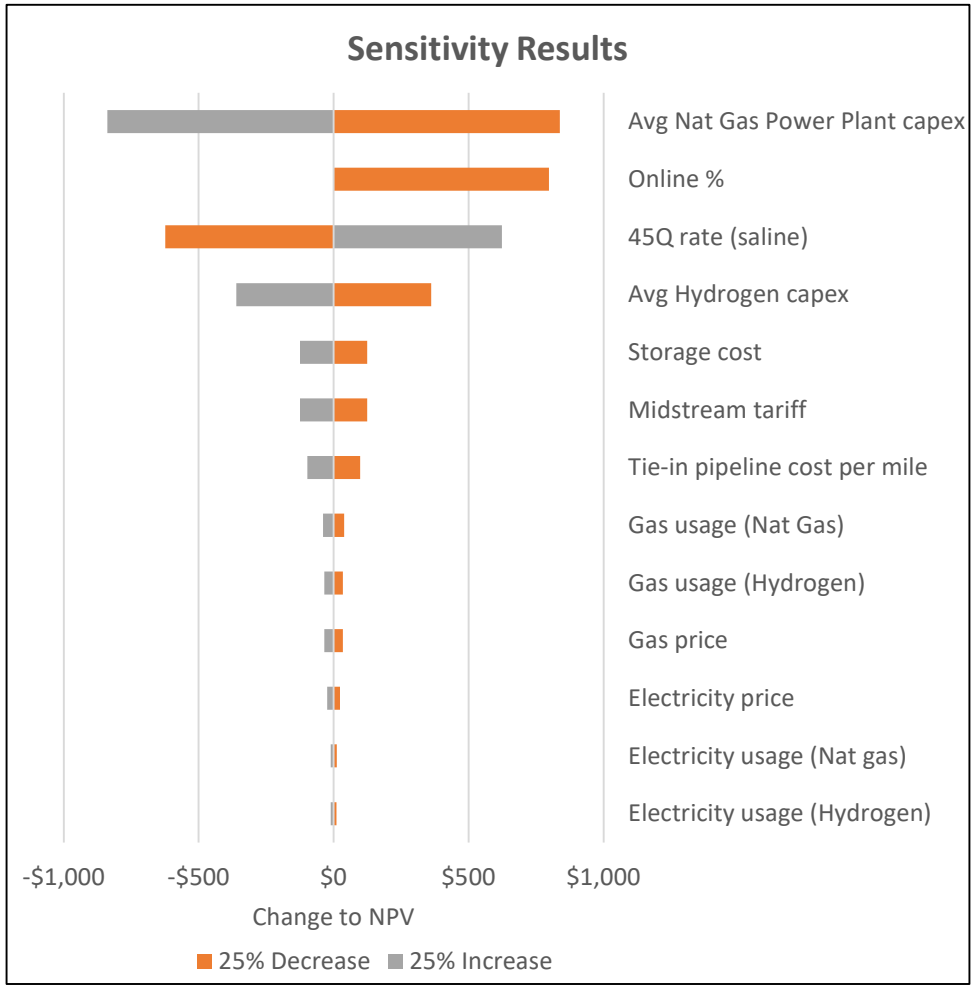
Natura

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

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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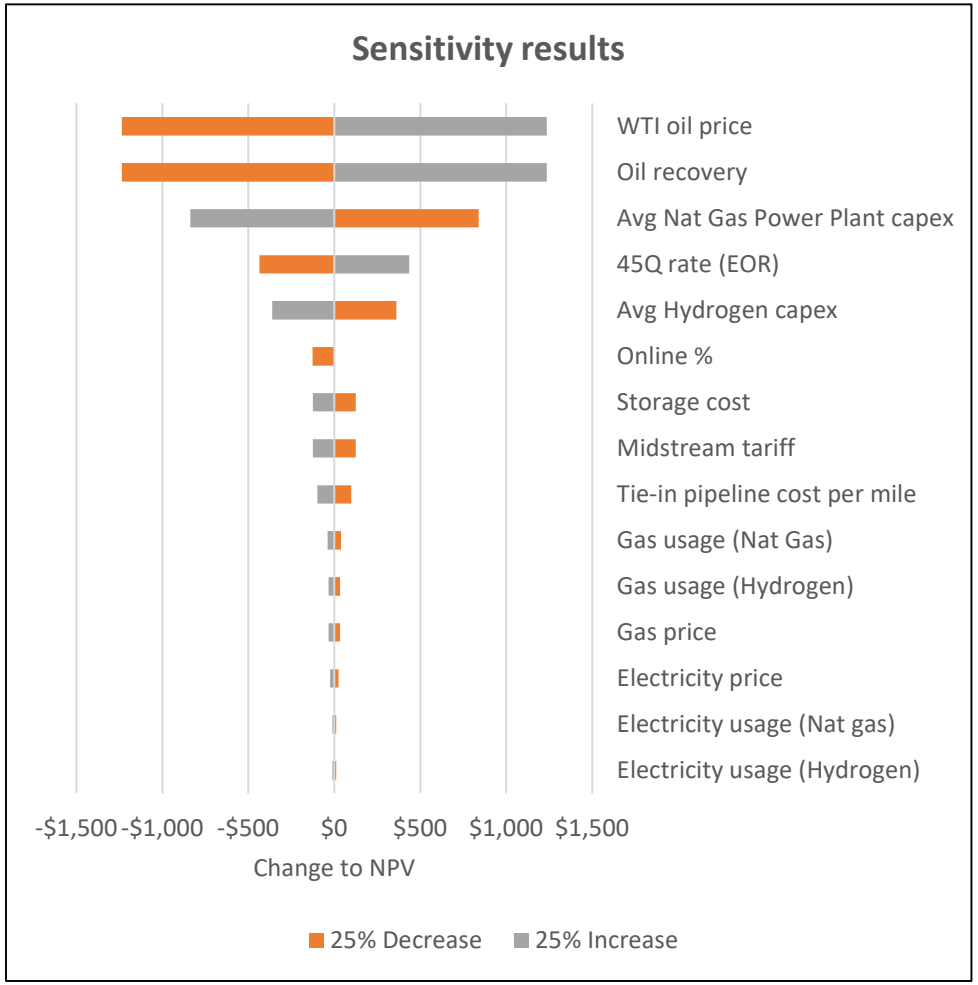
Phase I: Economic Model Results

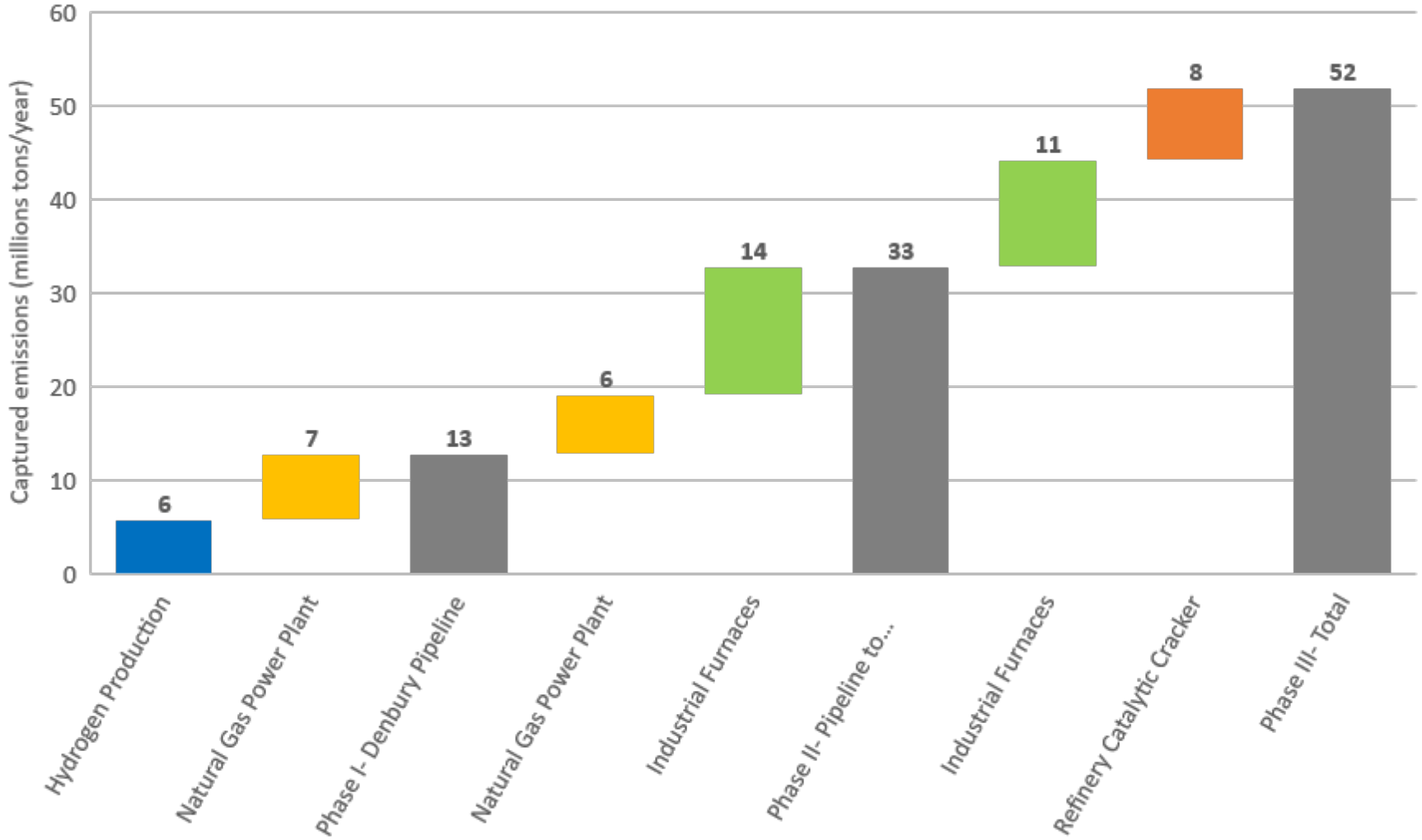
Combined hydrogen and natural gas power plant model – **100% EOR**

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**

Phase II: Expansion – FW Basin and Offshore



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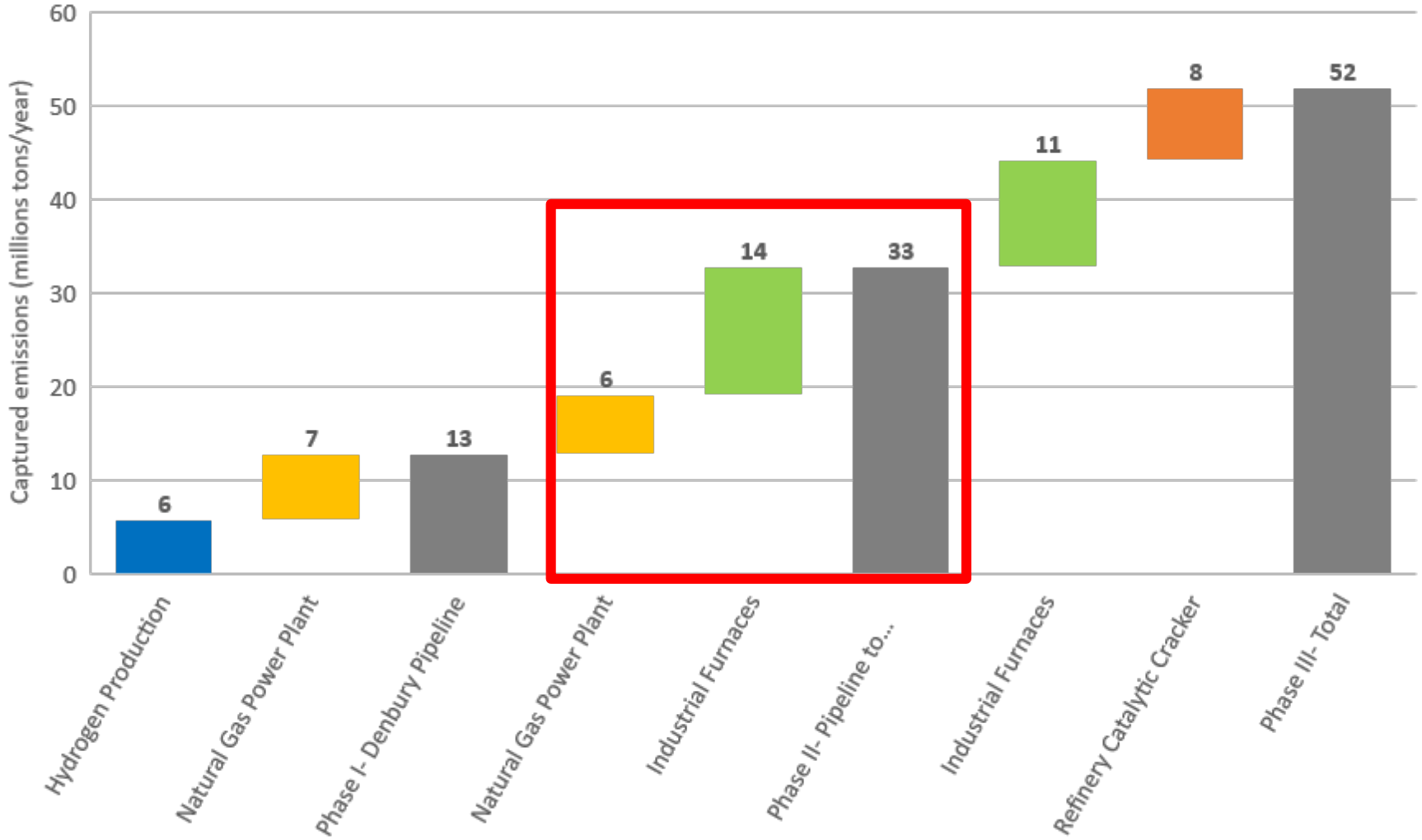


Phase II: Expansion (2040)

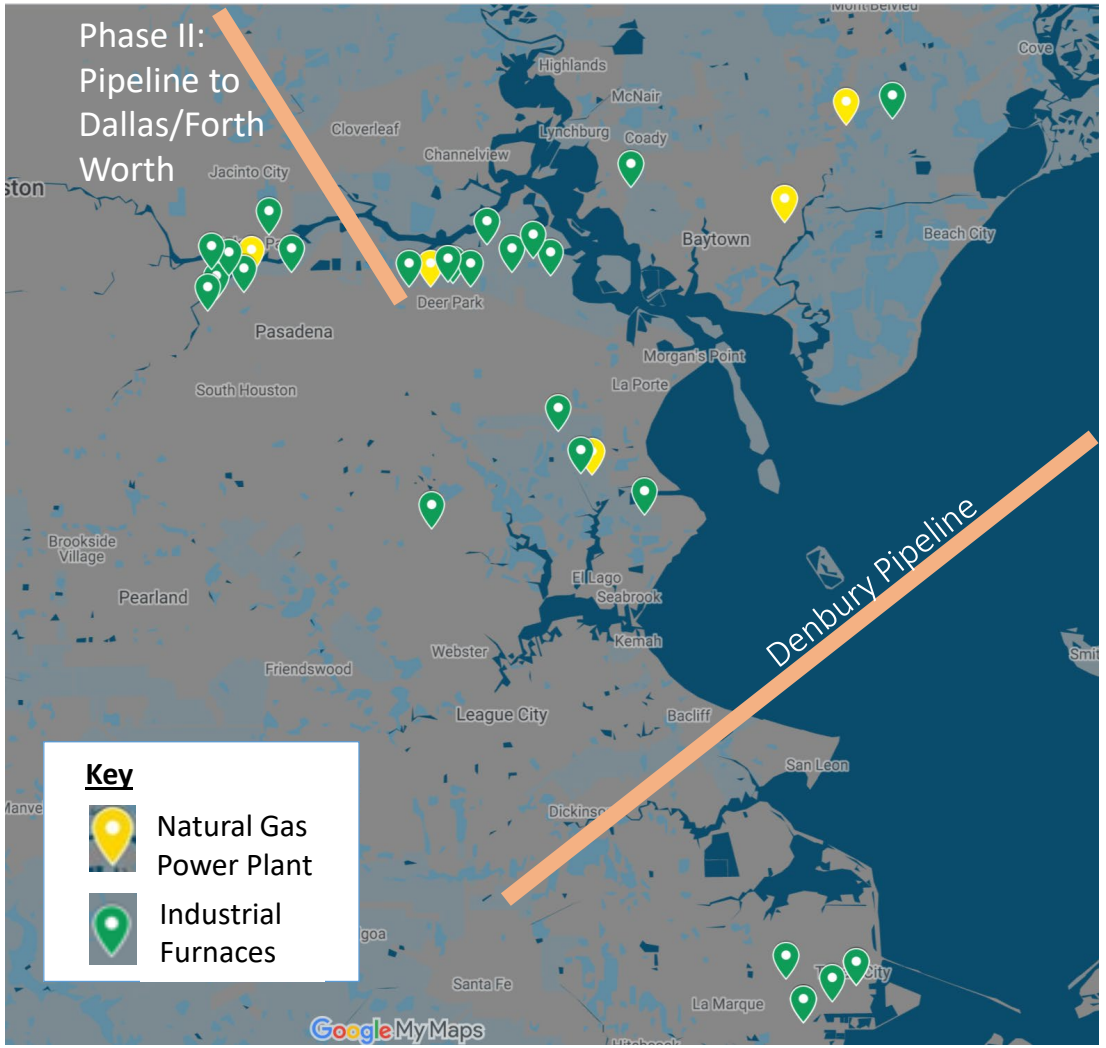
Capture

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 CO2
- Additional **Natural Gas Power Plants** are involved in the expansion of capacity transportation

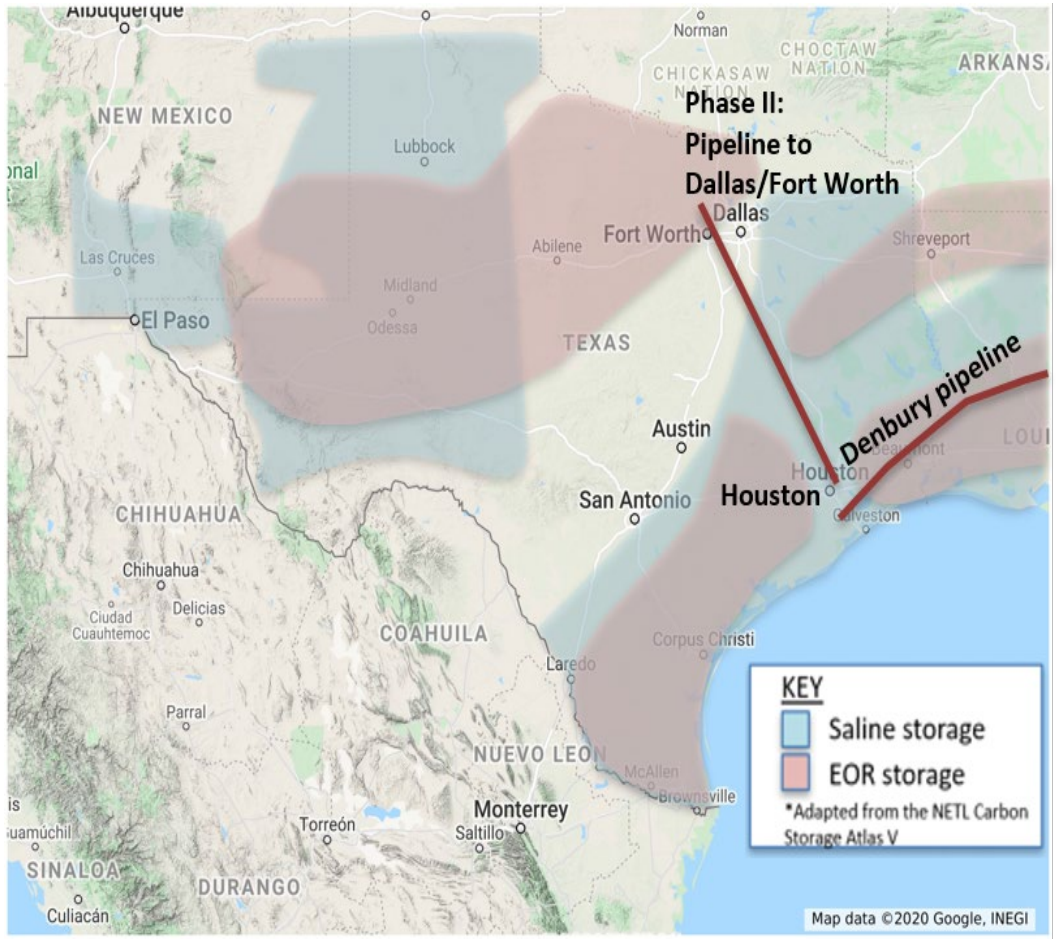


Phase II: Expansion (2040)

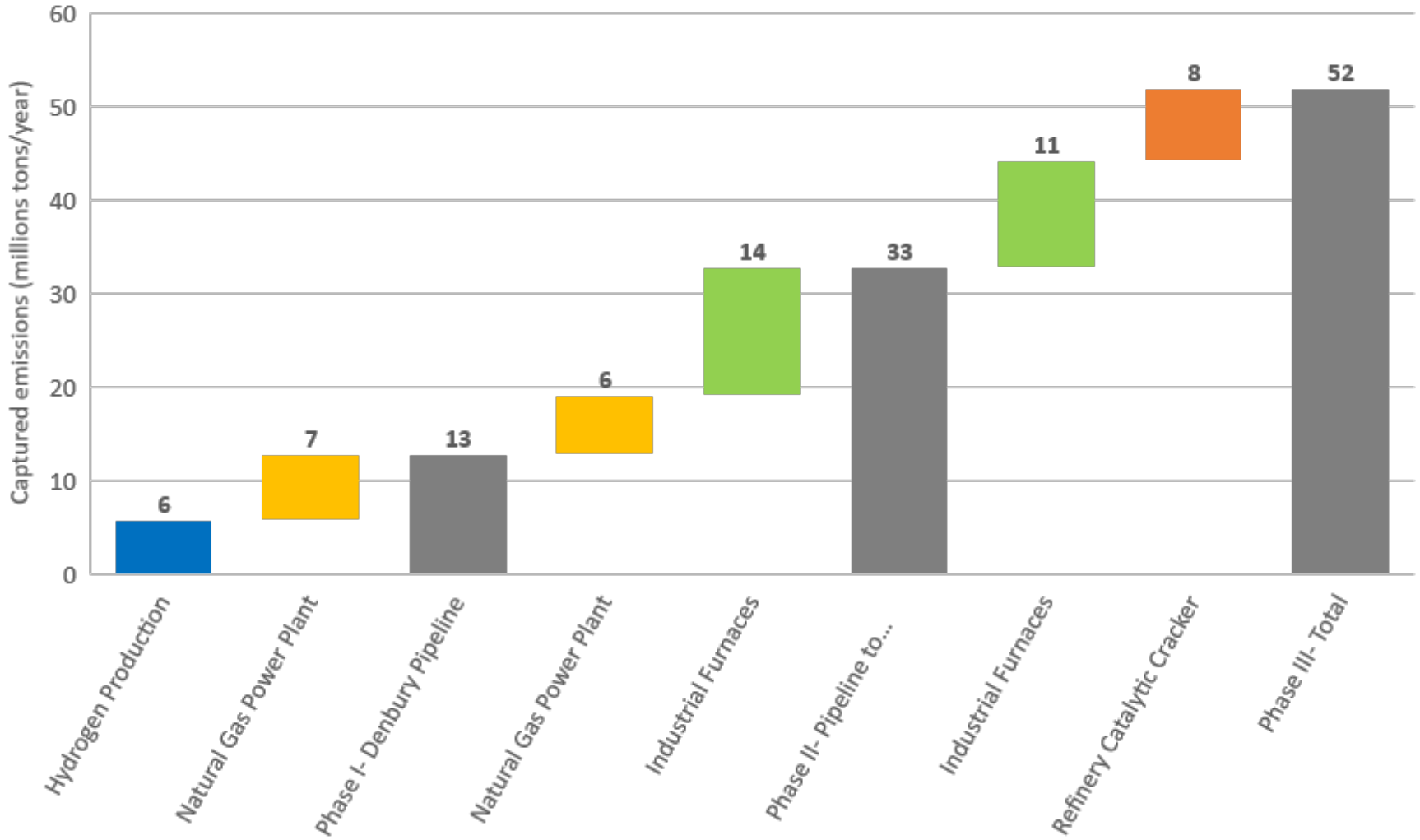
Storage

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**



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



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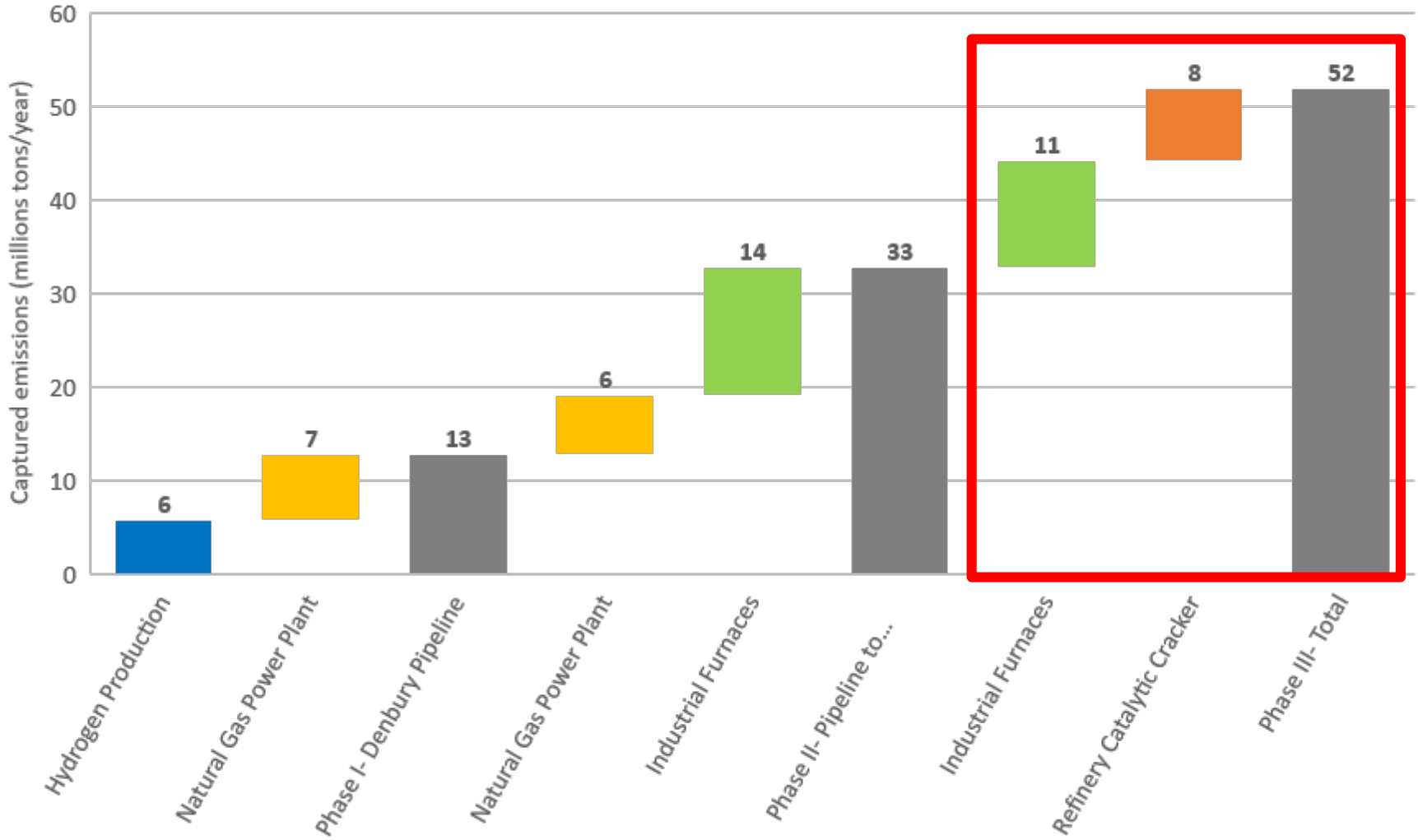


Phase III: At-Scale (2050)

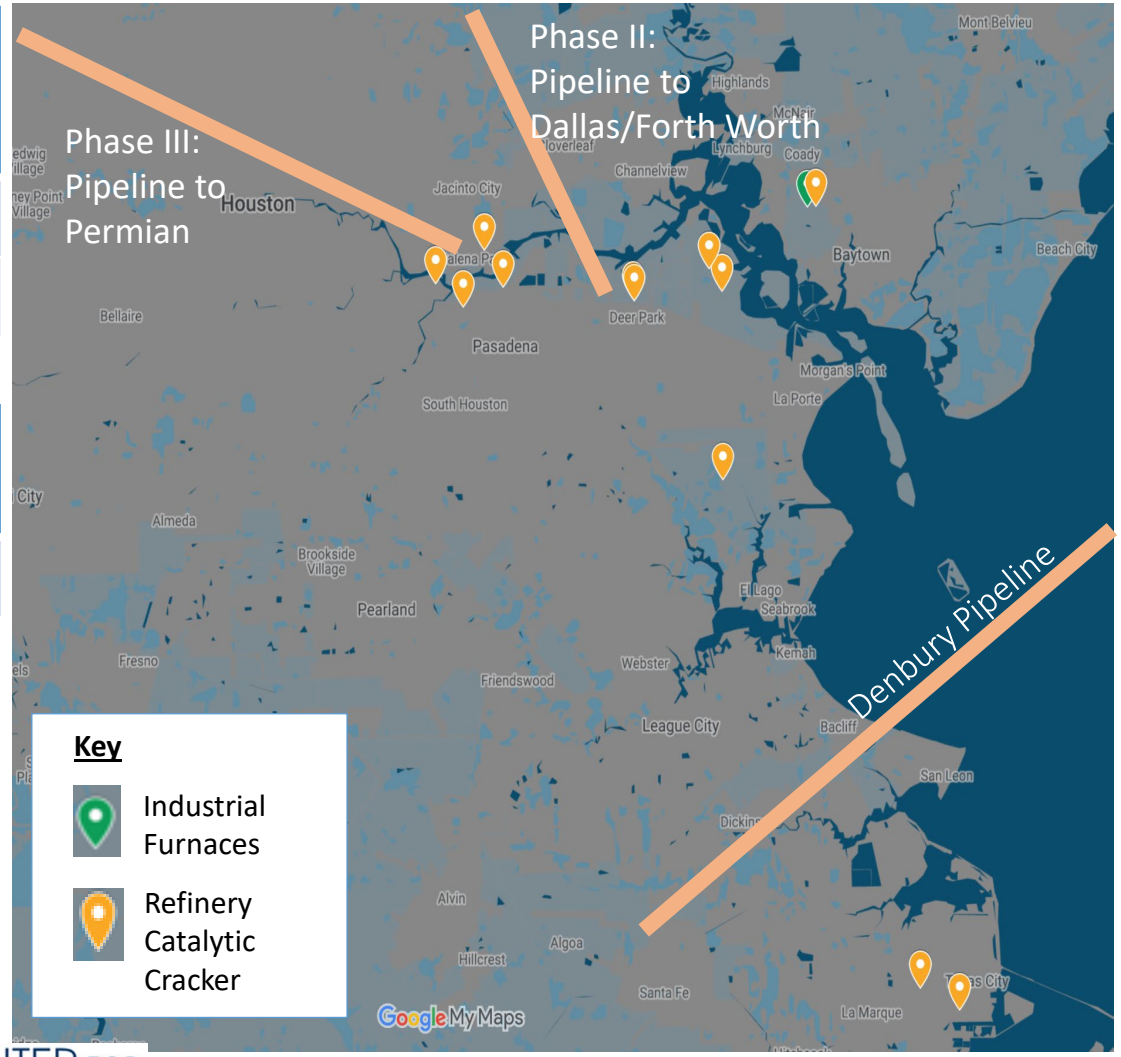
Capture

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 CO2
- Projected pipeline from Houston to the Permian Basin will **help with the economic feasibility of both carbon capture and pipeline projects**

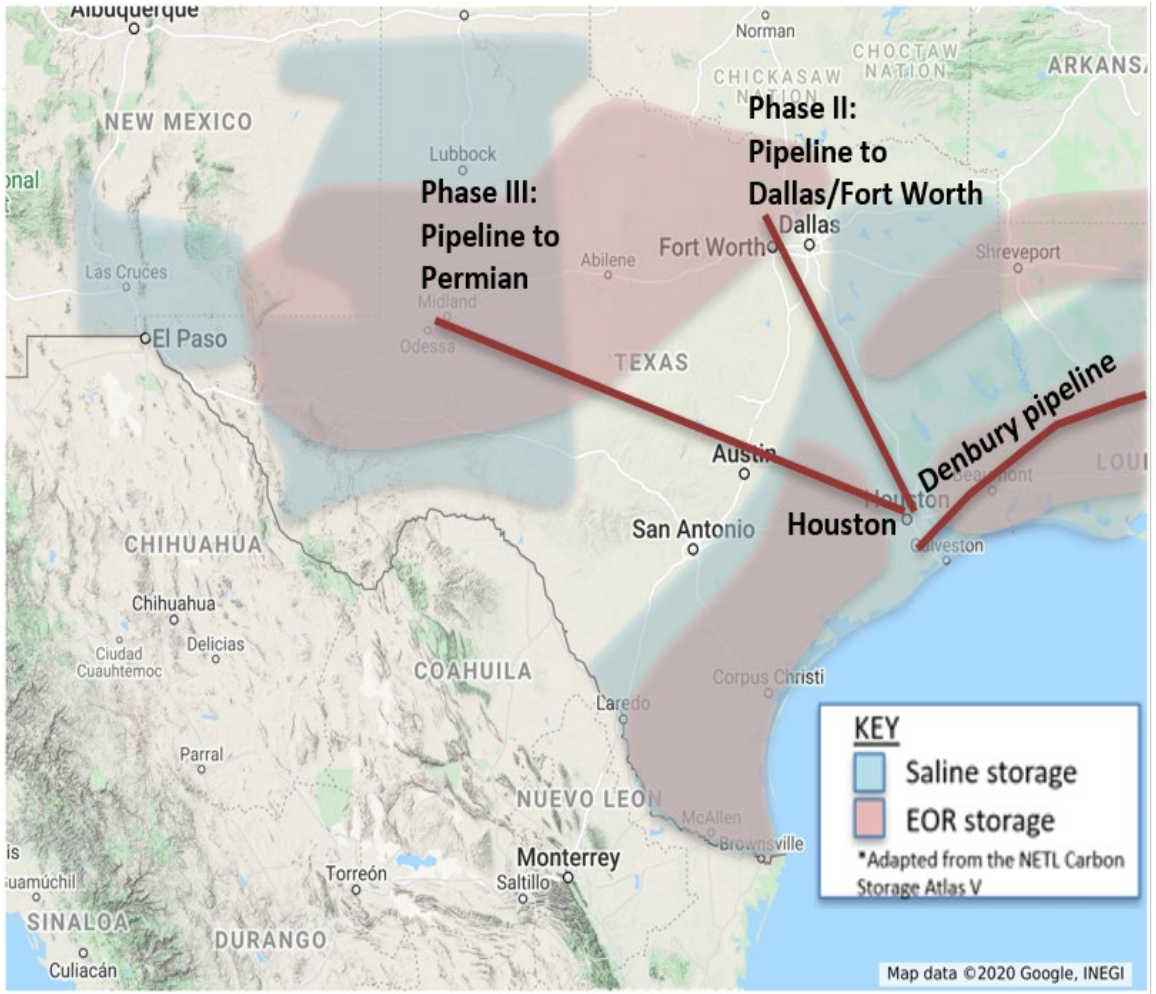


Phase III: At-Scale (2050)

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**



Key Takeaways

- **Phase I (present to 2030):**
  - **Focus on Low cost strategic CO2 Houston emissions:** 5.7million tons/yr from Hydrogen
    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

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- **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

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- **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

Pathway to a Low Carbon Electricity Grid

Current Assets & Issues

- TX Wind: 30 GW – highest in US
- TX Solar: 4 GW – 5th in US
- Mismatch with load profile
- Daily and seasonal variations
- "Must-run" CO_2 emitting resources (online coal units, cogeneration units) for capacity and load balancing.

Future Potential

- 80% zero carbon (55% wind, 19% solar, 6% nuclear) by 2050 without energy storage.
- CO_2 intensity declines 78%, from 850 lb/MWh to 191 lb/MWh.
- Energy storage needed for further decarbonization.
- Green H_2 storage most likely to be cost-effective.

The Houston Region as a Global Hydrogen Hub

Current Assets & Issues

- Produces ~⅓ of US hydrogen
- 900 miles of hydrogen pipelines (½ of US and ⅓ of world totals)
- Substantial geologically unique salt cavern storage capacity
- Serves Gulf Coast refining and petrochemical operations

Future Potential

- Add CCUS to SMR (Blue Hydrogen). Reduces CO_2 emissions by 15 Mton/y.
- Develop electrolytic (green) hydrogen with renewable electricity from TX grid.
- Develop H_2 trucking, other apps.
- Develop storage
- Export hydrogen

Houston and the Circular Plastic Economy

Current Assets & Issues

- Major producer – e.g., 80% of US PVC manufactured in Texas and Louisiana
- CO_2eq emissions for Houston area – 30 million metric tons (2015)
- Unmanaged waste – 5% of plastics worlwide

Future Potential

- Advanced recovery, reclamation and recycling.
- Initial focus: single-use plastics; expand to other applications, supported by policies & incentives.
- Deploy chemical recycling (solvolysis and pyrolysis).
- By 2030: Recycle 2.5 Mton/y; eliminate 10 MMt CO_2eq/y; Create 15,000 jobs.
- By 2050: Increase benefits 3x

Acknowledgements

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Thank you!