Role of CO_2 EOR for Carbon Management

Prepared for:
Carbon Management Workshop

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Midland, TX

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Our history of services:

Since 1971*, we have added value to hundreds of oil and gas E&P projects in the U.S. and in over 30 countries, from Australia to Zimbabwe.

Our approach integrates geology and geophysics, petroleum engineering, and strategic and economic analysis.

We specialize in enhanced oil and gas recovery and the geological storage of CO_2.

*From 1971 – 1987, the company was called Lewin & Associates; from 1987 – 1991, the company was a subsidiary of ICF Consulting/Kaiser Engineers; since 1991, the company is stand alone and called Advanced Resources International, Inc.

Our clients include:

Introduction

I will introduce my talk by addressing five <u>assertions</u> on the viability of CCUS and its role in carbon management:

1. CO_2 EOR provides, at best, a niche opportunity for carbon management.
2. Storing CO_2 and producing oil with CO_2 EOR adds to the carbon management problem.
3. CO_2 EOR with associated CO_2 storage is a high cost option not viable at near-term oil prices.
4. CO_2 EOR with associated CO_2 storage can meet essentially all CO_2 storage needs.
5. The costs and challenges of CO_2 capture will severely limit available CO_2 supplies, even with 45Q tax credits.

Assertion #1: CO_2 EOR Provides, at Best, a Niche Opportunity for Carbon Management

Response #1: Not so!

- The technically viable CO_2 storage capacity offered by applying CO_2 EOR to conventional onshore oil fields and to the Permian Basin's residual oil zone (ROZ) is 83,600 million metric tons, enabling 1,000 million metric tons (40% of CO_2 emissions from domestic point sources) to be stored for 84 years.
- Adding potential CO_2 storage capacity from applying CO_2 EOR to offshore oil fields and shale oil formations would notably increases these numbers.
- Nine of the ten large-scale CCUS projects active in the U.S. involve CO_2 EOR; five of the nine large international CCUS projects involve CO_2 EOR.

Assertion #2: Storing CO_2 and Producing Oil with EOR Adds to the Carbon Management Problem

Response #2: Not so!

- The demand for oil, not the supply of oil, primarily governs how much oil is used and combusted.
- A barrel of oil produced using CO_2 EOR and associated CO_2 storage displaces a barrel of oil produced conventionally with no storage of CO_2.
- CO_2 EOR can store more CO_2 than the CO_2 contained in a barrel of oil when combusted.
  - CO_2 content of a barrel of oil is 0.43 metric tons; with 12% used for chemicals and other products, the combusted portion of a barrel of oil provides 0.38 metric tons of CO_2 per barrel.
  - For CO_2 EOR, the injected CO_2 to oil produced ratio for economically viable projects is 0.46 to 0.48 metric tons per barrel.

Assertion #3: CO_2 EOR With Associated CO_2 Storage Is a High Cost Option Not Viable at Near-Term Oil Prices

Response #3: Not so!

- At a $60/B oil price and a $25/mt CO_2 price (delivered), the economically viable CO_2 storage capacity offered by applying CO_2 EOR to conventional onshore oil fields and the ROZ is about 37 million metric tons, enabling 500 to 1,000 metric tons (20% to 40% of CO_2 emissions from domestic point sources) to be stored for 37 to 74 years.
- The U.S. Energy Information Administration's AEO 2019 projects oil prices of $78/B (WTI) by 2025 and $100/B by 2040 (2018 $/B), although oil prices in AEO 2020 will likely be about $20/B lower.
- "Next Generation" CO_2 EOR technology, involving advanced reservoir characterization conformance practices and real-time feedback and control methods, would notably improve CO_2 EOR performance and its economic viability.

Assertion #4: CO_2 EOR with Associated CO_2 Storage Can Meet Essentially All CO_2 Storage Needs

Response #4: Not so!

- Significant volumes of point source CO_2 emissions exist in the Northeast, the Mid-Atlantic, the Southeast portions of the country.
- The great bulk of the CO_2 EOR potential exists west of the Louisiana/Mississippi state line, particularly in West Texas, requiring long distance CO_2 trunklines from CO_2 sources to oil fields.
- Meanwhile, “world class” CO_2 storage opportunities exist in geologic (saline) formations in the SE and Gulf Coast areas of the country close to CO_2 sources.
- CO_2 EOR and geologic (saline) formations will likely provide equal volumes of CO_2 storage for CO_2 capture.

Assertion #5: The Costs and Challenges of CO_2 Capture Will Severely Limit Available CO_2 Supplies, Even with 45Q Tax Credits

Response #5: Not so!

- Some CO_2 capture projects (the "low hanging fruit") will be viable under the current 45Q structure, but not enough.
- Improvements to the 45Q tax credit, such as extending the time period of the credit to 20 years and providing other support, can make retrofit of existing coal-fired power plants with CO_2 capture and addition of CO_2 capture to new NGCC plants economically viable providing significant volumes of CO_2 supply*.
- Access to capital and support for first of kind (FOAK) projects will also be important.
- Incorporating CCUS, with CO_2 EOR and with geologic storage, will provide a notably lower cost carbon management solution than without CCUS.

*Esposito, R.A., Kuuskraa, V.A., Rossman, C.G., and M.M. Corser, 2019, Reconsidering CCS in the US fossil-fuel fired electricity industry under section 45Q tax credits, Wiley Publications, Greenhouse Gases: Science and Technology, Modeling and Analysis, https://onlinelibrary.wiley.com/doi/full/10.1002/ghg.1925, 11 September 2019.

Introduction

The utilization of captured CO_2 emissions for enhanced oil recovery (EOR) provides numerous benefits:

- Increased domestic oil production, particularly once shale/tight oil production peaks,
- Safe secure storage of CO_2, with much of the oil field infrastructure already in place, and
- A source of revenues for captured CO_2 emissions.

The questions are –

- ***Is utilization of CO_2 for EOR a niche or a major opportunity?***
- ***Just how large and varied is the "prize"?***
- ***To what extent will Section 45Q tax credits boost captured CO_2 supplies for EOR?***

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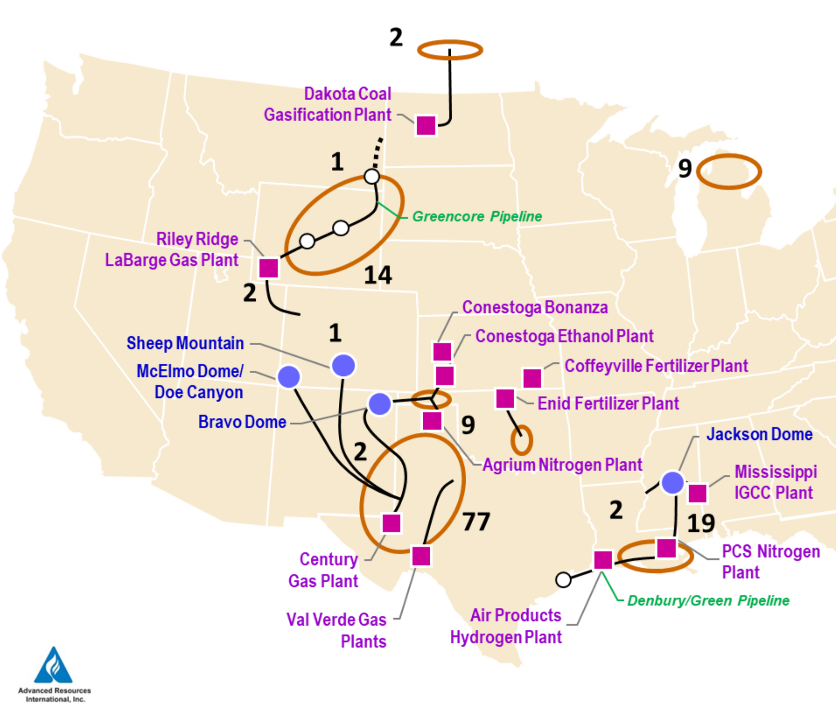
Status of CO_2 EOR: A Snapshot in Time

The development of large natural sources of CO_2 (e.g., McElmo Dome, Jackson Dome, etc.) established the foundation for the CO_2-EOR industry. Capture of industrial sources of CO_2 will be essential for supporting growth.

Current CO_2 EOR Operations and CO_2 Sources (2014/2019)



Oil Production (2014)	
CO_2-EOR Projects	136
Oil Production (MBbl/d)	300
CO_2 Supplies (2019)	
Number of Sources	17
• *Natural*	*5*
• *Industrial*	*12*
CO_2 Supply (Bcf/d)	3.3
• *Natural*	*2.2*
• *Industrial*	*1.1*

136	No. of U.S. CO_2-EOR Projects
●	Natural CO_2 Source
■	Industrial CO_2 Source
———	CO_2 Pipeline
....	CO_2 Proposed Pipeline

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- Based on the 2014 O&GJ Survey, 136 significant CO_2 EOR projects currently produce 300,000+ barrels per day in the U.S. by injecting 3.3 Bcfd of CO_2, <u>with 1.2 Bcfd from industrial sources</u>.
- In spite of limitations in supplies of CO_2 and lower oil prices, existing CO_2-EOR projects are being expanded and new CO_2 EOR projects started.

Source: Advanced Resources International based on Oil & Gas Journal and other industry data, 2014/2019.

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Capturing CO_2 from Industrial Facilities for EOR

Currently, 22 million metric tons of industrial/power plant CO_2 emissions are captured and used annually for domestic enhanced oil recovery.

		MMMt/Yr.
▪	Power Plants (Petra Nova)	1.4
▪	Fertilizer Plants	1.7
▪	Hydrogen Plants	1.0
▪	Ethanol Plants	1.1
▪	Gas Processing Plants	16.8
	Total	**22.0**

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An additional 3 MMmt/yr. of CO_2 is captured at the Northern Great Plains Coal Gasification Plant and transported to Canada for EOR at the Weyburn/Midale oil fields.

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Boundary Dam and Alberta Carbon Trunk Line

Since 2014, SaskPower's Boundary Dam Power Station has captured and sold to the EOR industry 2 million metric tons of CO_2.

Source: SaskPower, 2018

By end of 2019, the 240 km Alberta Carbon Trunk Line (ACTL) will transport 1.5 million mt of CO_2 per year captured from the Redwater Fertilizer plant and NW Redwater's Sturgeon Refinery for use and storage with EOR.

At full capacity, the ACTL will provide access to reservoirs capable of storing 14.6 million metric tons per year.

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PetraNova: "Poster Child" of Carbon Utilization

PetraNova has installed post combustion CO_2 capture on a 240 MW coal-fired unit at the WA Parish power plant near Houston, Texas.

The 80 MMcfd of captured CO_2 is transported and used for EOR at Hilcorp's West Ranch oil field with an oil production goal of 15,000 B/D.

Source: NRG, 2017

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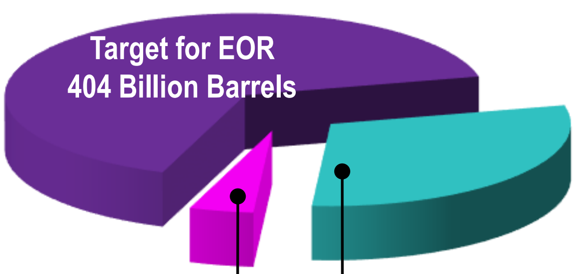
The Conventional Onshore CO_2-EOR Prize

In the U.S., primary recovery and water flooding have recovered about a third of the 614 billion barrel onshore oil endowment, leaving behind 404 billion barrels.

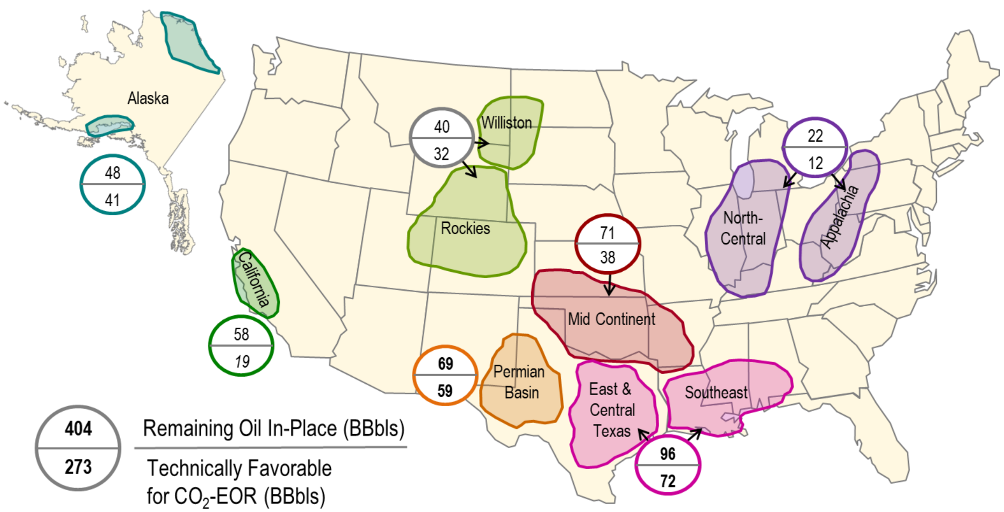
Much of this "left behind oil", equal to 273 billion barrels, is technically favorable for CO_2-EOR and is widely distributed across the U.S.

Original Oil In-Place: 614 B Barrels
Remaining Oil In-Place: 404 B Barrels



*Does not include "tight" oil production or reserves.
Source: Advanced Resources International, 2015.

Conventional Onshore Domestic Oil Resources Favorable for CO_2-EOR



Source: Advanced Resources International internal analysis, 2016

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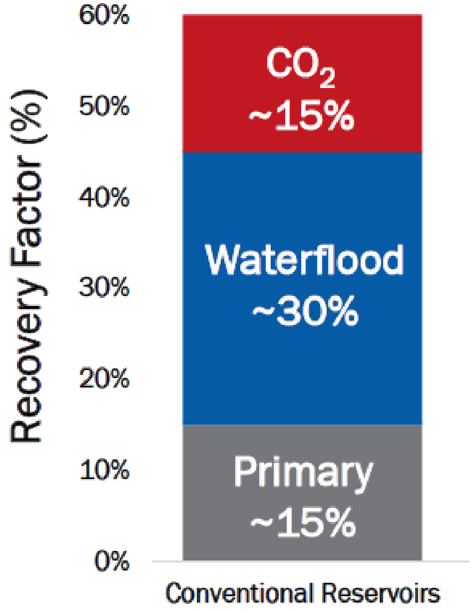
CO_2-EOR Performance

While relatively simple in concept, successful application of CO_2-EOR entails sophisticated design, process/flow modeling, and continuous monitoring.

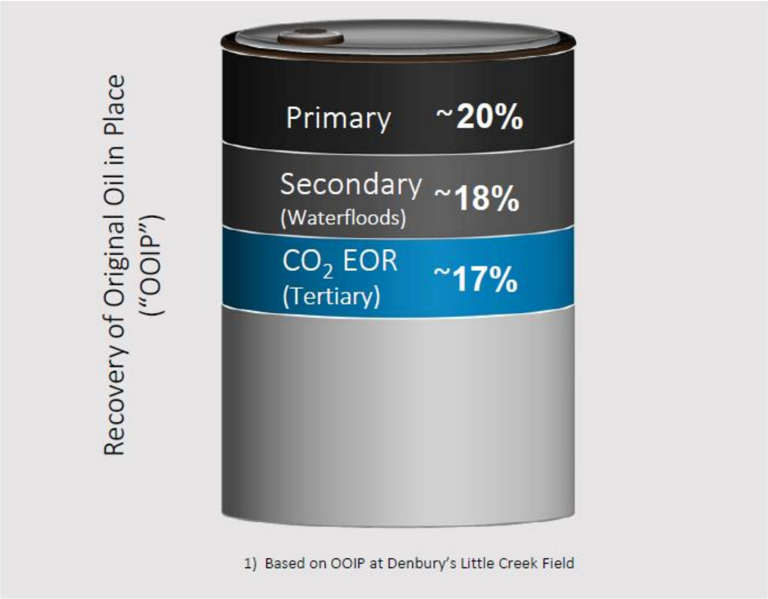
Recovery of OOIP – Permian Basin



Source: Oxy, 2017.

In the Permian Basin, CO_2 EOR can recover 15% of OOIP.

Recovery of OOIP - - Gulf Coast



Source: Denbury Resources, 2018.

In Gulf Coast oil fields, CO_2-EOR can produce as much oil as primary or secondary recovery.

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Conventional Oil CO_2 EOR

Our assessment of the conventional oil CO_2 EOR "prize" is based on a data base of over 2,000 onshore oil reservoirs. It involves evaluating the technical and economic potential of each of these oil reservoirs using our CO_2 EOR PROPHET stream-tube simulator and our CO_2 EOR economics model.

At an oil price of $60/barrel and with "best practices" technology, CO_2 EOR offers the potential for 38 billion barrels of economically viable oil recovery creating 18,300 million mt of demand (and storage) for CO_2, for a CO_2 injected to oil produced ratio of 0.48 mt per barrel.

Basin/Area	OOIP Favorable for CO_2 EOR	Technically Recoverable Oil (Billion Barrels)	Technical Demand for CO_2 (Million Metric Tons)	Economically Recoverable Oil* (Billion Barrels)	Economic Demand For CO_2* (Milion Metric Tons)
Lower-48 Onshore	232	72	38,400	33	16,000
Alaska	41	9	4,600	5	2,300
Total	**273**	**81**	**43,000**	**38**	**18,300**

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*At an oil price of $60/B (WTI), a CO2 price of $25 per metric ton, and 15% ROR (before tax).
Source: "Improving Domestic Energy Security and Lowering CO2 Emissions with "Next Generation" CO2-Enhanced Oil Recovery (CO2-EOR)", DOE/NETL-2011/1504, July 2011, prepared by Advanced Resources International, Inc., updated in 2019 by Advanced Resources International, Inc.

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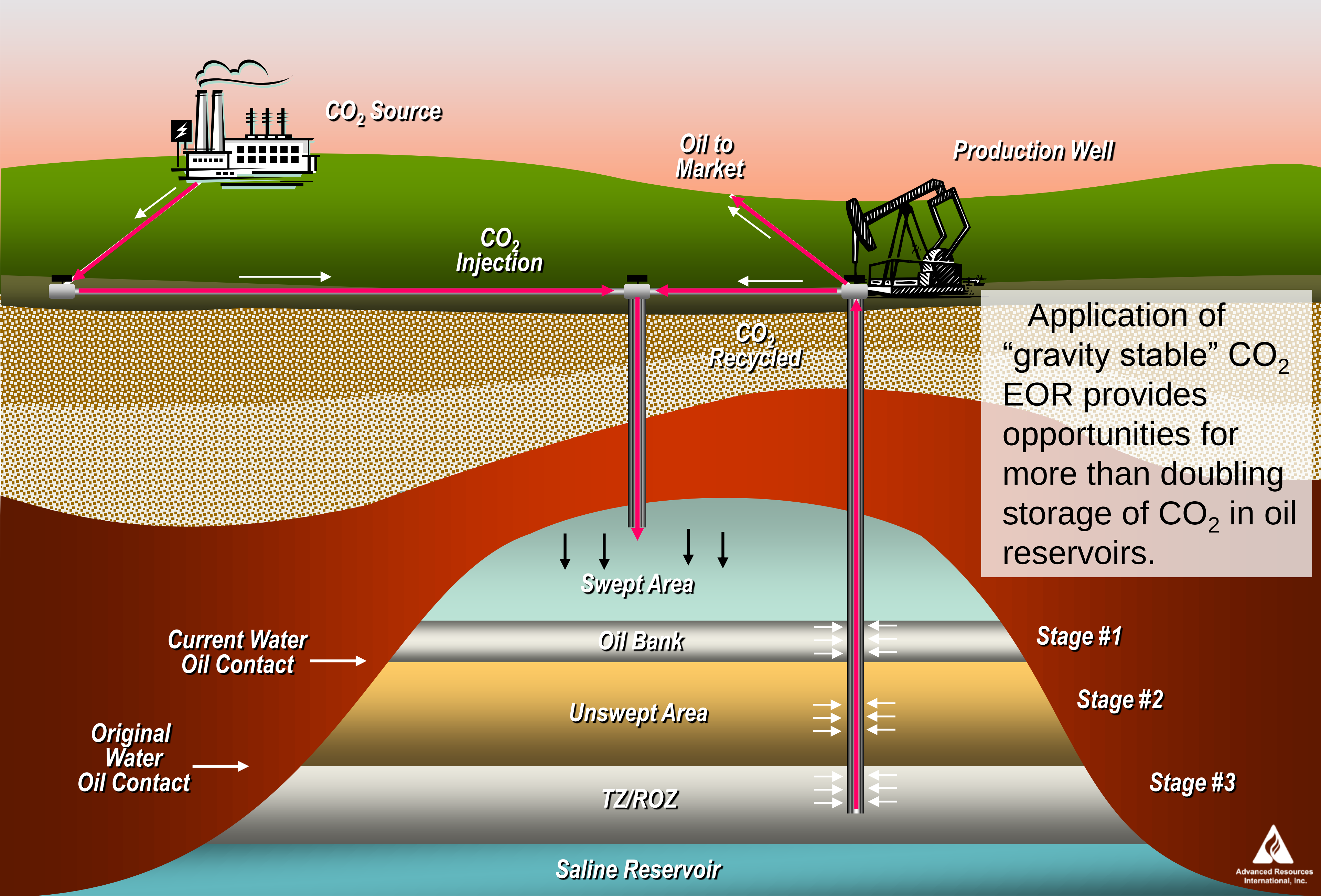
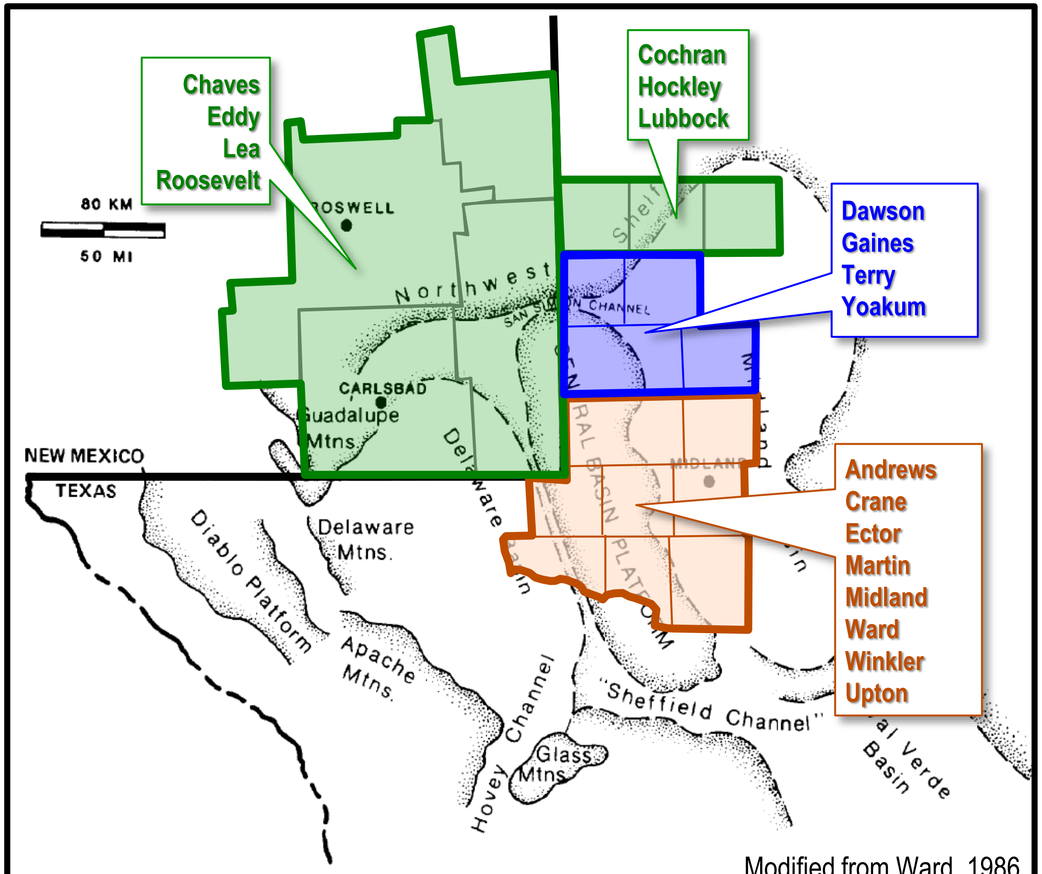
“Next Generation” CO_2 EOR and Storage Technology



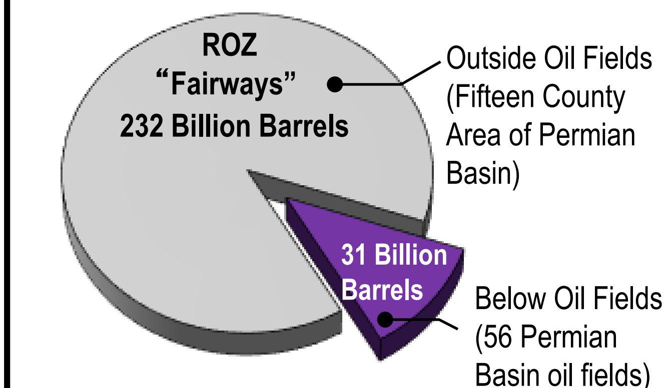
Application of “gravity stable” CO_2 EOR provides opportunities for more than doubling storage of CO_2 in oil reservoirs.

ROZ CO_2 EOR and Demand (Storage) for CO_2

Advanced Resources assessment of the San Andres Fm ROZ resource in the Permian Basin of West Texas and SE New Mexico.



Over 260 Billion Barrels of Oil "Left Behind" in Residual Oil Zones (ROZs)



Source: Advanced Resources International, 2018.

The "ROZ fairway" resource assessment entailed analysis of <u>384 logs</u>, <u>use of core data from 10 locations</u>, and <u>construction of 95 regional cross-sections</u>.

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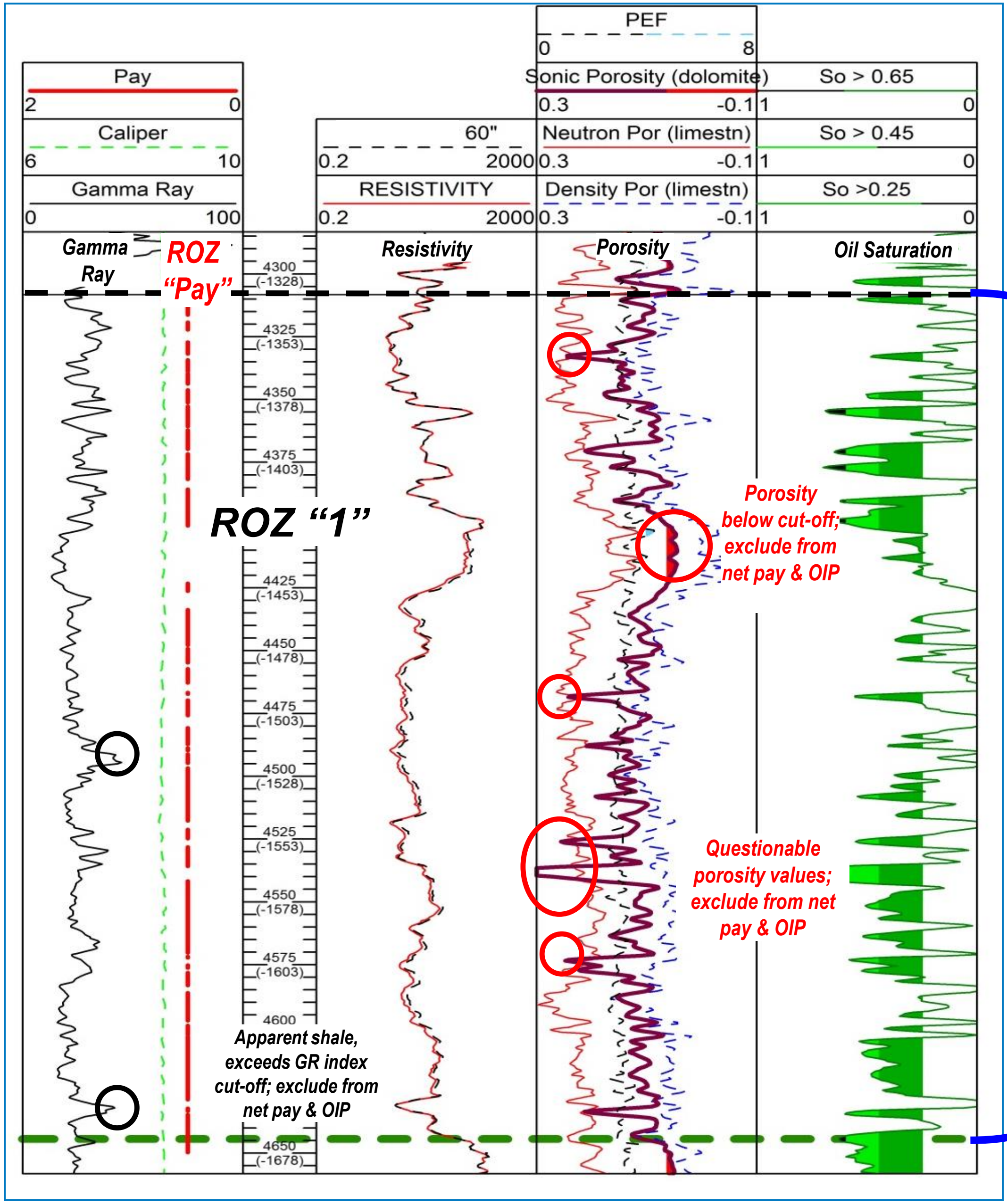
Log Analysis for Computing Oil In-Place



The Upper ROZ in Gaines County, Texas (location of KM's Tall Cotton ROZ Project) has thick net pay (259 ft) with 30% (average) oil saturation.

ROZ 1

Gross Pay = 336'

Net Pay = 259'

Porosity = 0.126

Oil Saturation = 0.30

OIP (B/AF) = 229

OIP (B/Acre) = 59,338

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Kinder Morgan's CO_2 EOR Investments

Kinder Morgan currently produces about 80,000 B/D (gross) of oil from CO_2 EOR. Much of Kinder Morgan's future CO_2 EOR investment targets the ROZ (Residual Oil Zone).

CO_2 Projects @ $60/B (WTI)

Project	IRR*
SACROC Conventional	44%
SACROC Transition Zone	52%
Yates Hz Wells	100+%
Tall Cotton ROZ	19%

*After tax.

Development Plan (2019-2028)

	10 Year Plan	
	Net BOE (MMBoe)	KM Share CapEX (MM)
SACROC Complex	65	$916
Yates Group	22	$162
Katz/GLSAU	9	$75
Tall Cotton ROZ	48	$1,556
CO2 S&T	-	$585
Total	**144**	**$3,294**

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San Andres ROZ “Fairway” CO_2 EOR

The San Andres ROZ “fairway” contains 232 billion barrels of OIP; 40 billion barrels is economically viable (at $60/B oil price), creating a demand (storage) for CO_2 of 18,400 million mt and a CO_2 injected to oil produced ratio of 0.46 per barrel.

	Oil In-Place	Technically Recoverable Oil	Technical Demand for CO2	Economically Recoverable Oil*	Economic Demand for CO_2
	(Billion Bbls)	(Billion Bbls)	(Million mt)	(Billion Bbls)	(Million mt)
West Texas	**194**	**55**	**35,800**	**34**	**15,400**
▪ 4 County Study [1]	104	28	20,000	17	8,000
▪ 8 County Study [2]	71	22	12,100	15	6,300
▪ 3 County Study [3]	18	5	3,700	2	1,100
New Mexico	**38**	**12**	**5,800**	**6**	**3,000**
Total**	**232**	**67**	**41,600**	**40**	**18,400**

*Using $60/B (WTI) oil price, a CO_2 cost of $25/mt, and 10% ROR (after tax). **Totals may not add due to rounding.

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1. “Defining an Overlooked Domestic Oil Resource: A Four-County Appraisal of the San Andres Residual Oil Zone (ROZ) “Fairway” of the Permian Basin” prepared by Advanced Resources International for U.S. DOE/NETL, 2016.
2. “San Andres ROZ “Fairway” Resources of the Permian Basin: An Eight-County Resource Assessment”, prepared by Advanced Resources International for U.S. DOE/NETL, 2016.
3. “Permian Basin San Andres ROZ Resources Assessment: West Texas and New Mexico” prepared by Advanced Resources International for U.S. DOE/NETL, 2018.

Geological CO_2 Storage Capacity

The CO_2 storage capacity in geologic formations (saline reservoirs) is vast, particularly along the Gulf Coast and the offshore of the Gulf of Mexico.

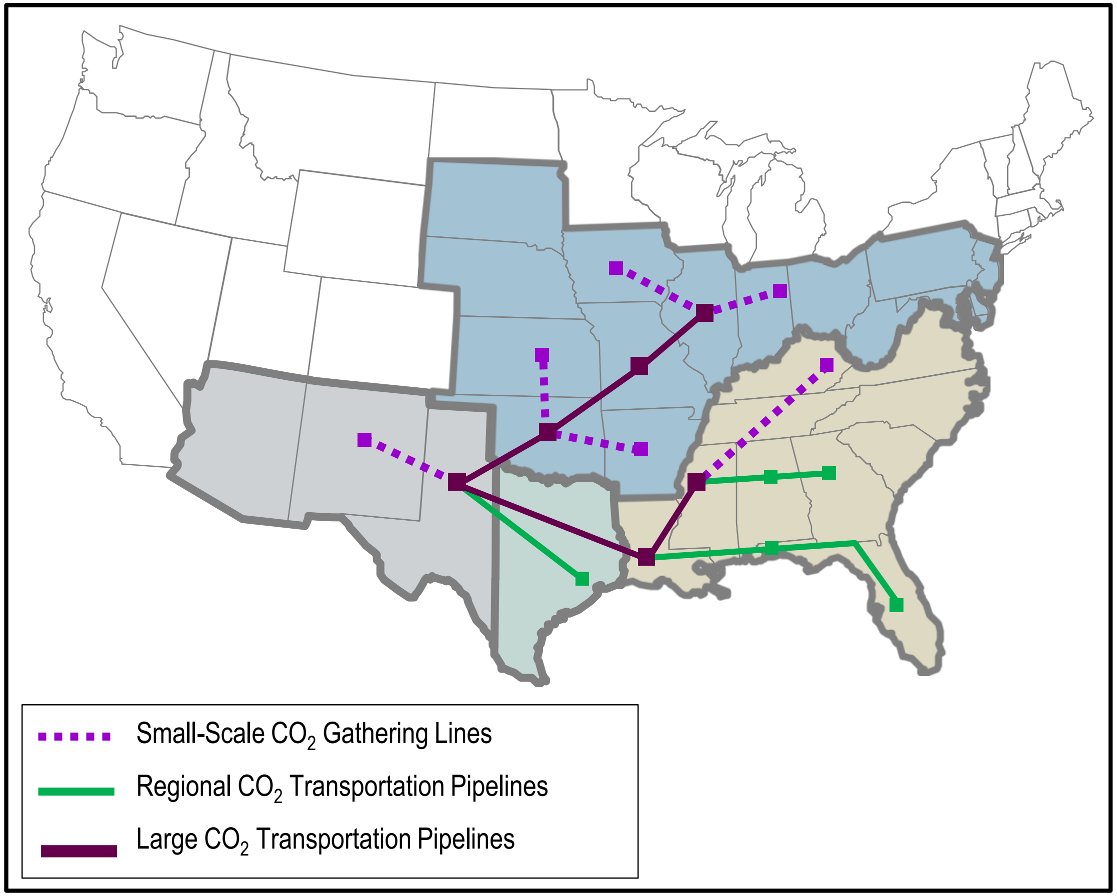
Our detailed appraisal of a “world class” quality geological storage site in east-central Mississippi (Kemper County) shows that a relatively small, 30,000 acre (50 mi^2) area has the capacity to store nearly 1,000 million metric tons of CO_2 in a series of three stacked saline formations.

High quality geologic formations close to CO_2 sources can offer low -- $2 to $3 per metric ton – costs for CO_2 storage*.

*Esposito, R.A., Kuuskraa, V.A., Rossman, C.G., and M.M. Corser, 2019, Reconsidering CCS in the US fossil-fuel fired electricity industry under section 45Q tax credits, Wiley Publications, Greenhouse Gases: Science and Technology, Modeling and Analysis, https://onlinelibrary.wiley.com/doi/full/10.1002/ghg.1925, 11 September 2019.

The Missing Link: CO_2 Transportation

Lack of CO_2 transportation between sources and oil fields is the critical "missing link" for producing oil and storing CO_2 with EOR.



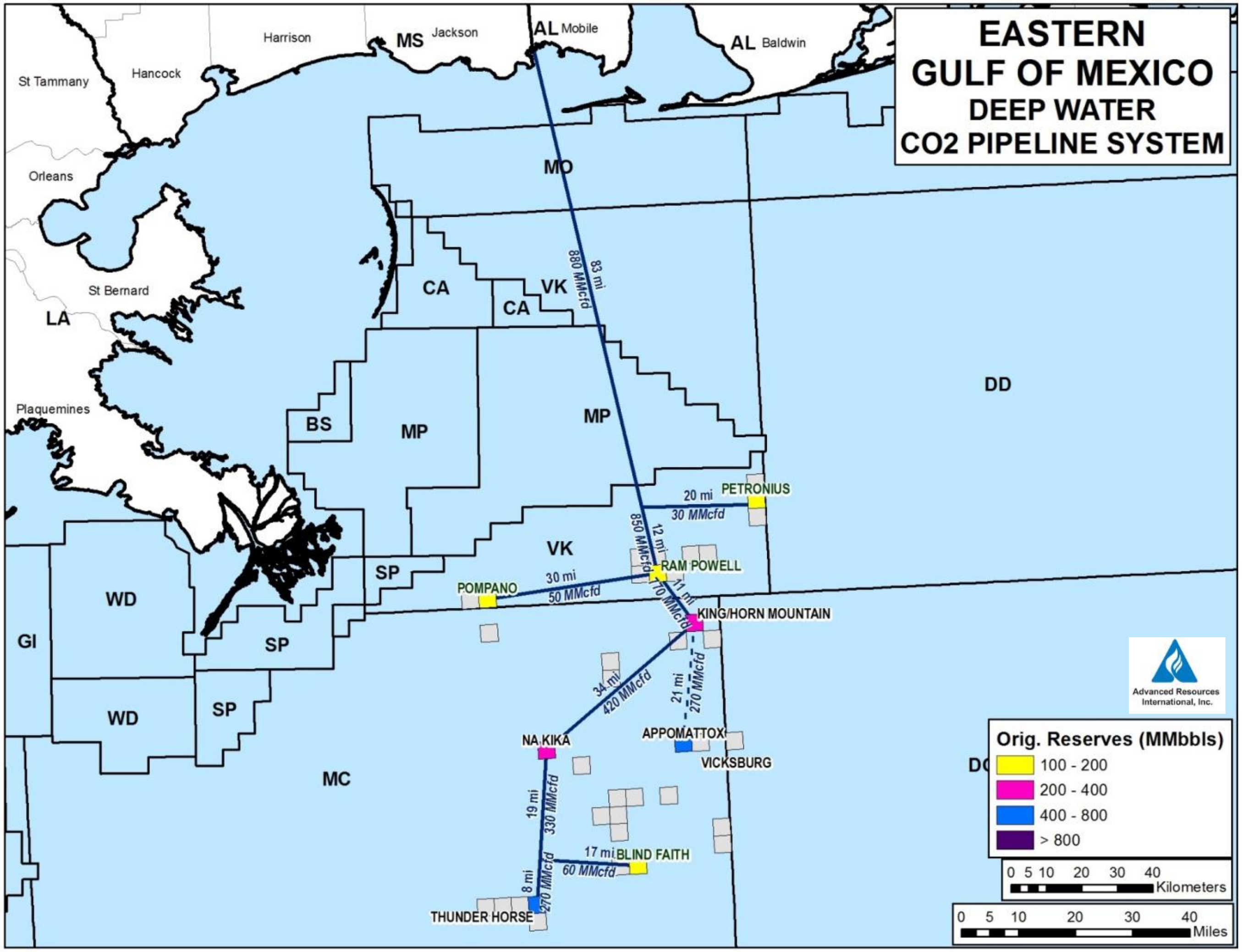
The study – **"Making Carbon a Commodity"** – proposed a comprehensive U.S. CO_2 pipeline system linking CO_2 captured from power plants with oil fields.

In Scenario #1,* the pipeline system would transport about 450 MMmt of CO_2 in Year 2040 and 950 MMmt of CO_2 in Year 2050.

*Scenario #1 represented the most aggressive CO_2 capture outlook for new coal- and gas-fueled power plants.

Source: Making Carbon a Commodity: The Potential of Carbon Capture RD&D (analysis by Advanced Resources International, 2018). Sponsored by the Carbon Utilization Research Council and ClearPath Foundation (2018).

Taking CO_2 EOR to the Deepwater Offshore GOM



Source: Advanced Resources International, 2018

Advanced Resources prepared a conceptual design for a Deepwater Gulf of Mexico CO_2 pipeline system.

The Eastern GOM Deepwater CO_2 Pipeline is a 255-mile system with an initial 83-mile line delivering 880 MMcfd (17 Mmt per year).

Additional large-scale CO_2 pipeline systems are needed to serve East-Central and Central Deepwater GOM.

Case Studies of Offshore GOM CO_2 EOR

Considerable study is underway on the CO_2 EOR and CO_2 storage potential offered by the offshore Gulf of Mexico.

Our case studies of two large offshore GOM deepwater oil fields – Cognac and Petronius – shows considerable potential for storing CO_2 with EOR:

	OOIP (MMB)	Primary/ Secondary Recovery (MMB)	CO_2 EOR Recovery (MMB)	CO_2 Storage	
				(Bcf)	(Mmt)
Petronius (J-2 Sand)	104	52	14	140	7
Cognac					
▪ Total Field J Sand	136	57	-	-	-
▪ NW Fault Block J Sand	24	9	8	37	2

The next step involves examining the economic viability of conducting CO_2 EOR in these two oil fields, particularly using advanced sub-sea technology.

A Look at an Emerging CO_2 EOR "Prize"

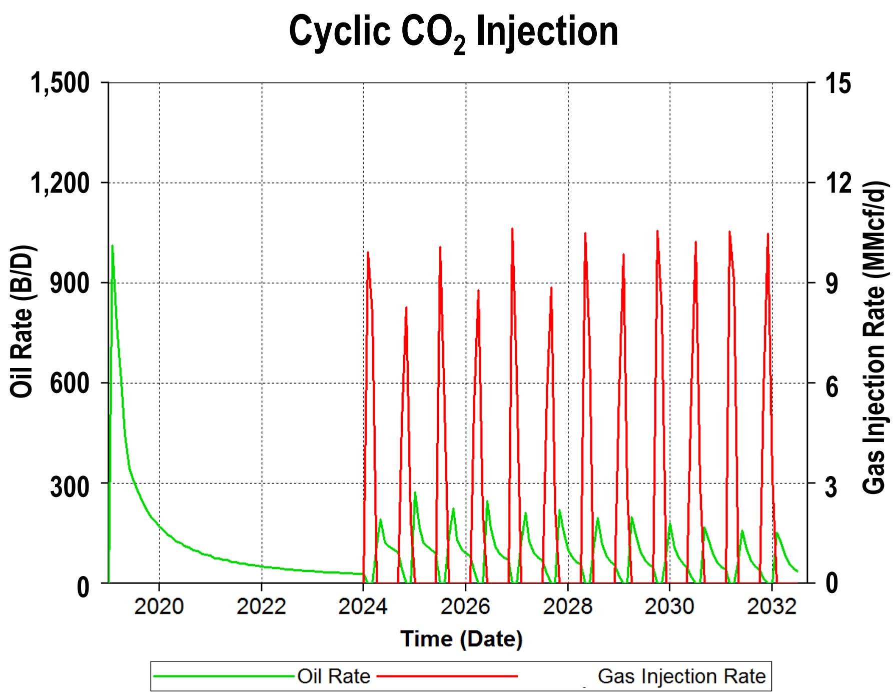
The most recent option for productively utilizing (and storing) CO_2 is for enhancing oil recovery from shale/tight oil.

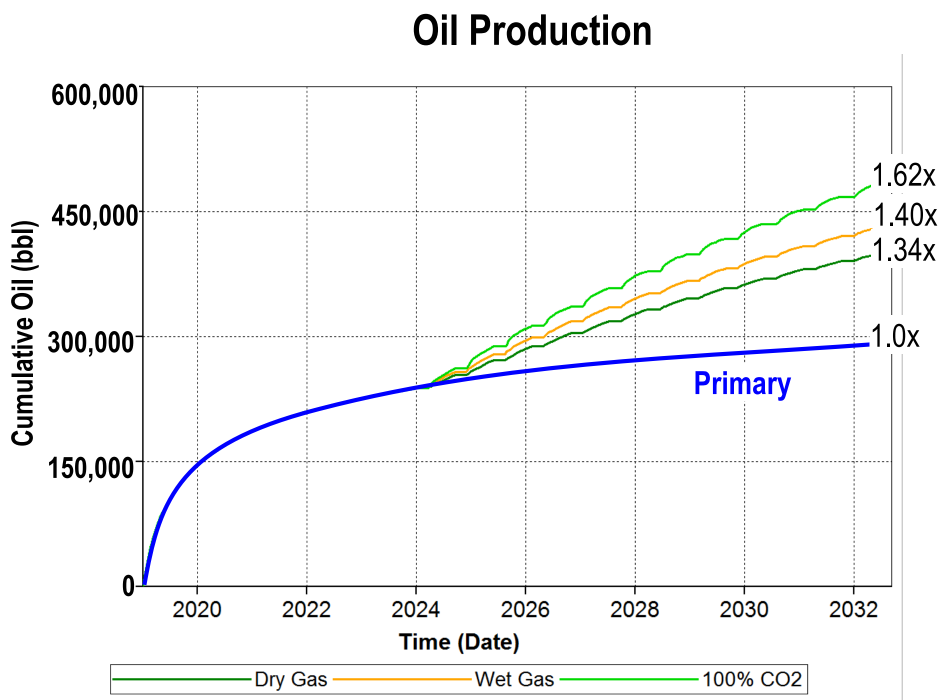
- Our compositional simulation (using GEM) for a "type" well in the central portion of the Eagle Ford Shale shows use of cyclic CO_2 injection would add 62% to oil recovery over primary methods.
- During the 12 cycles of CO_2 injection and production, an incremental 185,000 barrels of oil was produced and 840 MMcf (44,000 mt) of CO_2 was stored.
- Adding a 13^{th} CO_2 injection cycle and closing the well enabled an additional 840 MMcf (44,000 mt) of CO_2 to be stored, providing a CO_2 stored to oil produced ratio of 9.1 Mcf/B (0.48 mt/B).

The use of cyclic CO_2 provided significantly better performance than use of cyclic dry or wet natural gas for shale/tight oil EOR.

Eagle Ford Shale - Modeling Cyclic CO_2 Injection

Cyclic CO_2 was initiated after five years of primary production. CO_2 was injected at about 10 MMcfd for 2 months (BHP limit of 7,000 psia), followed by 2 weeks of soak, and by 6 months of production.





Source: Advanced Resources International, 2019.

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CO_2 Capture from an Illustrative Coal-Fueled Unit with 45Q Tax Credit

	Coal-Fueled EGU	
	No Capture	Capture with $50/tonne value
Heat Rate (MMBtu/MWh)	10	13
Cost of Fuel ($/MWh)	20	26
Variable O&M ($/MWh)	5	6
Total Incremental Cost ($/MWh)	25	32
CO_2 Capture (tonne/MWh)	-	1.09
Value of Captured CO_2 ($/MWh)	-	54
Value of Electricity When Generating ($/MWh)	30	25
Net Margin When Generating ($/MWh)	5	47
Generation of Electricity (MM MWh/yr)	2	3
Net Revenue Margin (million $ / yr)	10	140
Change in net annual margin relative to No Capture (million $ / yr)		+130

Installation of CO_2 capture increases the incremental power generation cost of the EGU from $25/MWh to $32/MWH; the EGU receives $54/MWh from 45Q.

With negative net costs per MWh, the EGU operates at 3 million MWh/year versus 2 million MWh/year without CO_2 capture.

The EGU now has a net annual revenue margin, $130 million per year higher than without CO_2 capture with a discounted (@ 7%) value of $1.1 billion (12 years) and $1.4 billion (20 years).

The capital costs of retrofit CO_2 capture for a 400 MW (net) SCPC plant is $1.1 to $1.2 billion plus $80 million for storage. In this example, CO_2 capture is marginally economically under 45Q.

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Concluding Observations

The opportunity for productively using (and storing) CO_2 for EOR (the "size of the prize") is vast – conventional onshore and offshore oil fields, the ROZ, and shale oil formations.

With a comprehensive CO_2 pipeline system (infrastructure) and stronger incentives for CO_2 capture, in our view CO_2 EOR could use (and store) 500 million metric tons annually in the Year 2040 to 2050 time period.

While the 45Q tax credit provides a valuable first step, extending the number of years of eligibility, beyond the current 12 years, and providing support for 1st of a kind (FOAK) projects will be required.

Doing so would enable large volumes of CO_2 to be cost-effectively captured from retrofit of coal-fueled power plants and from installation of CO_2 capture on new NGCC power plants.*

*Esposito, R.A., Kuuskraa, V.A., Rossman, C.G., and M.M. Corser, 2019, Reconsidering CCS in the US fossil-fuel fired electricity industry under section 45Q tax credits, Wiley Publications, Greenhouse Gases: Science and Technology, Modeling and Analysis, https://onlinelibrary.wiley.com/doi/full/10.1002/ghg.1925, 11 September 2019.

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