Role of CO$_2$ EOR for Carbon Management

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CO$_2$-EOR Technology: A Closed-Loop System

- **Purchased CO$_2$**: Anthropogenic and/or Natural Sources
- **Injected CO$_2$**: 
  - CO$_2$ Dissolved (Sequestered) in the Immobile Oil and Gas Phases
  - CO$_2$ Stored in Pore Space
- **Recycled CO$_2$ from Production Well**: Additional Oil Recovery

**Zone of Efficient Sweep**

- Immobile Oil
- Driver Water
- Miscible Zone
- Oil Bank
- Water
- CO$_2$
CO₂-EOR Performance

While relatively simple in concept, successful application of CO₂-EOR entails sophisticated design, process/flow modeling, and continuous monitoring.

Recovery of OOIP – Permian Basin

- Waterflood: ~30%
- Primary: ~15%
- CO₂: ~15%


In the Permian Basin, CO₂ EOR can recover 15% of OOIP.

Recovery of OOIP - - Gulf Coast

- Primary: ~20%
- Secondary (Waterfloods): ~18%
- CO₂ EOR (Tertiary): ~17%


In Gulf Coast oil fields, CO₂-EOR can produce as much oil as primary or secondary recovery.
The development of large natural sources of CO₂ (e.g., McElmo Dome, Jackson Dome, etc.) established the foundation for the CO₂-EOR industry. Capture of industrial sources of CO₂ will be essential for supporting growth.

Based on the 2014 O&GJ Survey, 136 significant CO₂ EOR projects currently produce 300,000+ barrels per day in the U.S. by injecting 3.3 Bcfd of CO₂, with 1.2 Bcfd (~ 22 million metric tons per year) from industrial sources.

In spite of limitations in supplies of CO₂ and lower oil prices, existing CO₂-EOR projects are being expanded and new CO₂ EOR projects started.

Source: Advanced Resources International based on Oil & Gas Journal and other industry data, 2014/2019.
Size of the US CO₂-EOR Prize

- 1/3 of the 624 billion barrel conventional oil endowment will be produced with primary/secondary technologies, leaving behind 414 billion barrels.
- Much of this “left behind oil” -- 284 billion barrels, is technically favorable for CO₂-EOR and is widely distributed across the U.S.
- At least 80 billion barrels is economic at today’s prices, and would require 40 billion metric tons of CO₂ to produce.

**Original Oil In-Place: 624 B Barrels**
**Remaining Oil In-Place: 414 B Barrels**

- **Target for EOR** 414 Billion Barrels
- **Proved Reserves** 20 Billion Barrels
- **Cumulative Production** 190 Billion Barrels

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

**Conventional Domestic Oil Resources Favorable for CO₂-EOR**

Source: Advanced Resources International internal analysis, 2016

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**Conventional Domestic Oil Resources Favorable for CO₂-EOR**

- **Remaining Oil In-Place (BBIs)**
- **Technically Favorable for CO₂-EOR (BBIs)**

Source: Advanced Resources International internal analysis, 2016
Potential CO₂ Sources

Potential Electric Generation CO₂ Sources
Above 1 Million Tonnes/Year

The Low-Hanging Fruit:
High Purity Stream Potential CO₂ Sources

Legend
Source
Electricity Generation

CO₂ Emissions (Metric Tons CO₂)
1,000,000 – 5,000,000
5,000,000 – 10,000,000
10,000,000 – 15,000,000
15,000,000 – 20,000,000+

Legend
High Purity Source
Ammonia
Ethanol
Ethylene Oxide
Hydrogen
Natural Gas Processing

CO₂ Emissions (Metric Tons CO₂)
100,000 – 500,000
500,000 – 1,000,000
1,000,000 – 1,500,000
1,500,000 – 5,000,000+

Our assessment of the conventional oil CO\textsubscript{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\textsubscript{2} EOR PROPHET stream-tube simulator and our CO\textsubscript{2} EOR economics model.

At an oil price of $60/barrel and with “best practices” technology, CO\textsubscript{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\textsubscript{2}, for a CO\textsubscript{2} injected to oil produced ratio of 0.48 mt per barrel.

<table>
<thead>
<tr>
<th>Basin/Area</th>
<th>OOIP Favorable for CO\textsubscript{2} EOR (Billion Barrels)</th>
<th>Technically Recoverable Oil (Billion Barrels)</th>
<th>Technical Demand for CO\textsubscript{2} (Million Metric Tons)</th>
<th>Economically Recoverable Oil* (Billion Barrels)</th>
<th>Economic Demand For CO\textsubscript{2}* (Million Metric Tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower-48 Onshore</td>
<td>232</td>
<td>72</td>
<td>38,400</td>
<td>33</td>
<td>16,000</td>
</tr>
<tr>
<td>Alaska</td>
<td>41</td>
<td>9</td>
<td>4,600</td>
<td>5</td>
<td>2,300</td>
</tr>
<tr>
<td>Total</td>
<td>273</td>
<td>81</td>
<td>43,000</td>
<td>38</td>
<td>18,300</td>
</tr>
</tbody>
</table>

*At an oil price of $60/B (WTI), a CO2 price of $25 per metric ton, and 15% ROR (before tax).

Wyoming has a total of 89 large oil fields viable for CO₂ EOR. These oil fields have a total of 12 billion barrels of OOIP. Incremental oil recovery of 2 billion barrels is technically viable with CO₂ EOR, requiring a total of 975 million metric tons of CO₂. Economically viable CO₂ EOR could recover 1.8 billion barrels of oil, requiring 844 million metric tons of CO₂.

<table>
<thead>
<tr>
<th>Oil Field Viability</th>
<th>Fields</th>
<th>OOIP (MMBbl)</th>
<th>Oil Recovery (MMBbl)</th>
<th>Purchased CO₂ (Bcf)</th>
<th>Purchased CO₂ (MMmt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technically Viable</td>
<td>89</td>
<td>12,030</td>
<td>2,100</td>
<td>18,430</td>
<td>975</td>
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<tr>
<td>Economically Viable*</td>
<td>60</td>
<td>10,470</td>
<td>1,810</td>
<td>15,960</td>
<td>844</td>
</tr>
</tbody>
</table>

*At an oil price of $60/bbl; CO₂ purchase price of $25/mt; 15% IRR before tax
North Dakota has a total of 42 large oil fields viable for CO₂ EOR. These oil fields have a total of 3.6 billion barrels of OOIP.

Incremental oil recovery of 770 million barrels is technically viable with CO₂ EOR, requiring a total of 339 million metric tons of CO₂.

Economically viable CO₂ EOR could recover 110 million barrels of oil, requiring 43 million metric tons of CO₂.

At an oil price of $60/bbl; CO₂ purchase price of $25/mt; 15% IRR before tax
Utah has a total of 17 large oil fields viable for CO₂ EOR. These oil fields have a total of 5 billion barrels of OOIP. Incremental oil recovery of 980 million barrels is technically viable with CO₂ EOR, requiring a total of 480 million metric tons of CO₂. Economically viable CO₂ EOR could recover 500 million barrels of oil, requiring 211 million metric tons of CO₂.
**Distribution of Benefits of CO₂-EOR**

<table>
<thead>
<tr>
<th>Notes</th>
<th>Description</th>
<th>CO₂-EOR Industry</th>
<th>Mineral Owners</th>
<th>Federal/State Treasuries</th>
<th>Power Plant/Other Capturers of CO₂</th>
<th>General Economy</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>NYMEX Oil Price</td>
<td>$80.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Transportation/Quality Differential</td>
<td></td>
<td>($3.00)</td>
<td></td>
<td>$3.00</td>
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<tr>
<td></td>
<td>Realized Oil Price</td>
<td></td>
<td></td>
<td></td>
<td>$77.00</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Less: Royalties</td>
<td>($13.10)</td>
<td>$10.90</td>
<td>$2.20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Production Taxes</td>
<td>($3.20)</td>
<td>($0.50)</td>
<td>$3.70</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>CO₂ Purchase Costs</td>
<td>($13.50)</td>
<td></td>
<td></td>
<td>$13.50</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>CO₂ Recycle Costs</td>
<td>($5.00)</td>
<td></td>
<td></td>
<td>$5.00</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>O&amp;M/G&amp;A Costs</td>
<td>($15.00)</td>
<td></td>
<td></td>
<td>$15.00</td>
<td></td>
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<tr>
<td>8</td>
<td>CAPEX</td>
<td>($7.00)</td>
<td></td>
<td></td>
<td>$7.00</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total Costs</td>
<td>($56.80)</td>
<td>$10.40</td>
<td>$5.90</td>
<td>$13.50</td>
<td>$30.00</td>
</tr>
<tr>
<td></td>
<td>Net Cash Margin</td>
<td>$20.20</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Income Taxes</td>
<td>($7.10)</td>
<td>($3.60)</td>
<td>$10.70</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Net Income ($/B)</td>
<td>$13.10</td>
<td>$6.80</td>
<td>$16.60</td>
<td>$13.50</td>
<td>$30.00</td>
</tr>
</tbody>
</table>

**CO₂-EOR provides a wide distribution of benefits:**

- Federal and state treasuries receive $16.60/Bbl, equal to $37/mt.
- The power industry receives $13.50/Bbl, equal to $30/mt.
- The U.S. economy receives $30/Bbl, supporting well-paying jobs and manufacturing.

1. Assumes an oil price of $80 per barrel (WTI) based on EIA AEO 2017 oil price for year 2022.
2. Assumes $3 per barrel for transportation.
3. Royalties are 17%; 1 of 6 barrels produced are from Federal and state lands.
4. Production and ad valorem taxes of 5% from FRS data.
5. CO₂ sales price of $30/metric ton including transport; 0.45 metric tons of purchased CO₂ per barrel of oil.
6. CO₂ recycle cost of $10/metric ton; 0.5 metric tons of recycled CO₂ per barrel of oil.
7. O&M/G&A costs from ARI CO₂-EOR cost models.
8. CAPEX from ARI CO₂-EOR cost models.
9. Combined Federal and state income taxes of 35%, from FRS data.

Source: Advanced Resources International internal study, 2017.
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)

- Outside Oil Fields (Fifteen County Area of Permian Basin) - 232 Billion Barrels
- Below Oil Fields (56 Permian Basin oil fields) - 31 Billion Barrels

The “ROZ fairway” resource assessment entailed analysis of 384 logs, use of core data from 10 locations, and construction of 95 regional cross-sections. Modified from Ward, 1986.
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.

The Missing Link: CO₂ Transportation

Lack of CO₂ transportation between sources and oil fields is the critical “missing link” for producing oil and storing CO₂ with EOR.

The study – “Making Carbon a Commodity” – proposed a comprehensive U.S. CO₂ pipeline system linking CO₂ captured from power plants with oil fields.

In Scenario #1,* the pipeline system would transport about 450 MMmt of CO₂ in Year 2040 and 950 MMmt of CO₂ in Year 2050.

*Scenario #1 represented the most aggressive CO₂ capture outlook for new coal- and gas-fueled power plants.

“Next Generation” CO$_2$-EOR and Carbon Negative Oil – Is it Possible?

- Most life-cycle analyses (LCA) of CO$_2$-EOR are based on historical operations:
  - Where CO$_2$ use was minimized per incremental barrel because of the high costs for CO$_2$
- Such LCAs often do not represent the emerging paradigm where CO$_2$ storage is a co-objective.
- Such LCAs often do not represent latest efficiencies in CO$_2$-EOR operations.
- Such LCAs often do not represent current refining operations.
  - An increasing portion of crude today is transformed into non-combustible products, like asphalt, lubricants, waxes, and chemical feedstocks.
Concluding Observations

- The opportunity for productively using (and storing) CO₂ for EOR (the “size of the prize”) is vast – conventional onshore and offshore oil fields, the ROZ, and shale oil formations.

- With a comprehensive CO₂ pipeline system and stronger incentives for CO₂ capture, in our view, CO₂ EOR could use (and store) 500 million metric tons annually in the 2040 to 2050 time period.

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

- Doing so would enable large volumes of CO₂ to be cost-effectively captured from retrofit of coal-fueled power plants and from installation of CO₂ capture on new NGCC power plants.

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.
Taking CO₂ EOR to the Deepwater Offshore GOM

Advanced Resources prepared a conceptual design for a Deepwater Gulf of Mexico CO₂ pipeline system.

The Eastern GOM Deepwater CO₂ Pipeline is a 255-mile system with an initial 83-mile line delivering 880 MMcf/d (17 Mmt per year).

Additional large-scale CO₂ pipeline systems are needed to serve East-Central and Central Deepwater GOM.
Application of “gravity stable” CO₂ EOR provides opportunities for more than doubling storage of CO₂ in oil reservoirs.