CO₂ Utilization with Enhanced Oil Recovery: The New Paradigm for CO₂ Capture and Storage

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Unconventional Resources • Enhanced Recovery • Carbon Sequestration
Introduction

To better understand the role of CO₂ enhanced oil recovery (CO₂-EOR) as a major carbon management strategy, it is useful to examine four key questions:

1. How ready are CO₂-EOR practices and technologies for large-scale CO₂ utilization?

2. To what extent can CO₂-EOR, like wind and solar, provide carbon neutral (“green”) energy?

3. What is the “size of the prize?” and

4. To what extent could CO₂-EOR provide a market-driven option for increased application of CO₂ capture?
1. How Ready Are CO\textsubscript{2}-EOR Practices and Technologies for Large-Scale CO\textsubscript{2} Utilization?

CO\textsubscript{2}-based enhanced oil recovery, using state-of-the-art (SOA) technology, is already being implemented in the U.S.:

- CO\textsubscript{2}-EOR currently provides about 284,000 barrels of oil per day.
- A total of 62 million metric tons of CO\textsubscript{2} was used by EOR last year with 13 million metric tons from industrial sources, natural gas processing plants, and hydrocarbon conversion facilities.
- A robust network of pipelines in the Permian Basin, the Gulf Coast and the Rockies transports this CO\textsubscript{2} to oil fields from natural CO\textsubscript{2} deposits, industrial sources and gas processing plants.
U.S. Oil Production from CO₂-EOR

With increased access to CO₂ supplies, CO₂-EOR production is expanding in the Gulf Coast and Rockies.
**Significant Volumes of Anthropogenic CO₂ Are Already Being Injected for EOR**

<table>
<thead>
<tr>
<th>Location of Oil Fields</th>
<th>Location of CO₂ Sources</th>
<th>CO₂ Supply</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Geologic</td>
</tr>
<tr>
<td>Texas, New Mexico, Oklahoma, Utah</td>
<td>Geologic (CO, NM) and Gas Processing, Fertilizer Plant (TX)</td>
<td>1,600</td>
</tr>
<tr>
<td>Colorado, Wyoming</td>
<td>Gas Processing (Wyoming)</td>
<td>-</td>
</tr>
<tr>
<td>Mississippi</td>
<td>Geologic (Mississippi)</td>
<td>930</td>
</tr>
<tr>
<td>Michigan</td>
<td>Gas Processing (Michigan)</td>
<td>-</td>
</tr>
<tr>
<td>Oklahoma</td>
<td>Fertilizer Plant (Oklahoma)</td>
<td>-</td>
</tr>
<tr>
<td>Saskatchewan</td>
<td>Coal Gasification (North Dakota)</td>
<td>-</td>
</tr>
<tr>
<td><strong>TOTAL (Million cfd)</strong></td>
<td></td>
<td>2,530</td>
</tr>
<tr>
<td><strong>TOTAL (Million metric tons/ year)</strong></td>
<td></td>
<td>49</td>
</tr>
</tbody>
</table>

* Source: Advanced Resources International, 2012

**MMcfd of CO₂ can be converted to million metric tons per year by first multiplying by 365 (days per year) and then dividing by 18.9 * 10^3 (Mcf per metric ton)**
New CO₂ pipelines and gas processing plants are delivering CO₂ to CO₂-EOR projects in the Gulf Coast and the Rockies.

- Green Pipeline
- Greencore CO₂ Pipeline
- Century Gas plant
- Lost Cabin Gas Plant

Source: Advanced Resources International, Inc., based on Oil and Gas Journal, 2012 and other sources.
CO\textsubscript{2}-EOR – Compelling Economics

![Bar chart showing WTI Breakeven Price for a 20% Before-Tax Rate of Return ($ per Bbl)]

$\begin{align*}
\text{WTI Breakeven Price for a 20\% Before-Tax Rate of Return ($ per Bbl)}^{(1)} \\
\$100 & \quad \$90 & \quad \$80 & \quad \$70 & \quad \$60 & \quad \$50 & \quad \$40 & \quad \$30 & \quad \$20 & \quad \$10 & \quad \$0 \\
\text{CO}_2\text{-EOR} & \quad \text{Hz. Mississippian} & \quad \text{Cara Woodford} & \quad \text{Eagle Ford Oil} & \quad \text{New Mexico Bone Spring} & \quad \text{Nobbara} & \quad \text{Texas Bone Spring} & \quad \text{Wolfcamp (Midland Basin)} & \quad \text{Wolfberry} & \quad \text{Bakken 600 More} & \quad \text{Bakken 400 More} \\
\$50 & \quad \$50 & \quad \$52 & \quad \$60 & \quad \$61 & \quad \$62 & \quad \$67 & \quad \$69 & \quad \$70 & \quad \$72 & \quad \$87 \\
\end{align*}$

(1) Source: KeyBanc as of 10/17/12. Defined as the threshold WTI oil price necessary to generate a 20\% before-tax rate of return. Excludes acreage costs.

(2) Internal estimate for indicative large CO\textsubscript{2} EOR development project in the Gulf Coast Region.

Source: Denbury Resources (2012)
Permian Basin CO₂-EOR Case Study

“What Does a Successful CO₂-EOR Project Look Like?”

- CO₂ injection into the Denver Unit of the giant Wasson (San Andres) oil field began in 1985.
- Before the start of CO₂-EOR, oil production had declined from 90,000 B/D to 40,000 B/D and was on pace to decline to below 1,000 B/D in the next 20 years.
- After the CO₂ flood, oil production rebounded to 50,000 B/D.
- Today, twenty four years later, the Denver Unit still produces 30,000 B/D.
**CO₂-EOR Results at the Denver Unit of the Wasson Oil Field**

- Begin CO₂ injection; departure from waterflood decline
- ~30,000 bopd
- ~700 bopd
Oil Recovery Performance From Permian Basin San Andres Formation

Permian Basin Typical Oil Recovery

- Remaining - 40%
- Primary - 10 to 15%
- Waterflood - 20 to 30%
- CO₂ Flood - 15%

Denver Unit, Wasson Field*

Oil Recovery

~2 Billion Barrel Oil OIP

- CO₂ Flood (19.5% OOIP)
- Waterflood (30.1% OOIP)
- Primary (17.2% OOIP)

Modified from Oxy (2009)

*Wasson Field: 2 Billion Barrels OOIP
Permian Basin CO₂-EOR Project Economics

“In the U.S., our Permian CO₂ operators continue to be our most profitable business, generating the highest free cash flow (after capital) among our entire portfolio of assets.”

Stephen Chazen
President and CEO
Occidental Petroleum
October 25, 2012

*$100/Bbl Marker Price
Source: Occidental Petroleum Corporation, May 2011
Opportunities for Improving CO₂-EOR Performance and Application

Even though CO₂-EOR already makes an important contribution, significant improvements are theoretically available in its performance and wider-scale application.

Some field projects, such as the CO₂-EOR floods at Denver Wasson and Weyburn, already practice selected aspects of “next generation” technology. However, with investments in research and field demonstrations, the contribution of CO₂-EOR -- to domestic energy security, to domestic CO₂ abatement, and to domestic revenues and economic well being -- could be much, much greater.

The following discussion of “next generation” CO₂ enhanced oil recovery summarizes both the opportunities and positive impacts of pursuing advances in CO₂-EOR technology.
“Next Generation” CO₂ Enhanced Oil Recovery

Use of more efficient CO₂-EOR technologies and extension of these technologies to new oil resources and settings constitutes “next generation” CO₂ enhanced oil recovery:

1. Scientifically-based advances in CO₂-EOR technology,
2. Integrating CO₂ capture with CO₂ utilization by CO₂-EOR,
3. Application of CO₂-EOR to residual oil zones (ROZs), and
“Next Generation” CO₂ Enhanced Oil Recovery

Six scientifically-based advances in CO₂-EOR technology:

1. Advanced reservoir characterization (to map residual oil and reservoir heterogeneity);
2. Combination horizontal/vertical wells plus “smart” well technology (to better contact bypassed oil);
3. CO₂ mobility and flow path control agents (to improve reservoir conformance);
4. Increased volumes of efficiently targeted CO₂ (to improve oil recovery efficiency);
5. Near-miscible CO₂-EOR technology (to expand CO₂-EOR to additional oil reservoirs); and
6. Advanced reservoir surveillance and diagnostics technology (to “see and steer” the CO2 flood).
Performance of CO₂ Flood Without Advanced Mobility and Conformance Control

Without advanced mobility and conformance control, much of the injected CO₂ will channel through a modest portion of the reservoir’s pore space.

<table>
<thead>
<tr>
<th>% Pore Space</th>
<th>% Injected CO₂</th>
<th>PV Throughput (1 HCPV of CO₂)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>75%</td>
<td>3.0</td>
</tr>
<tr>
<td>20</td>
<td>16%</td>
<td>0.8</td>
</tr>
<tr>
<td>20</td>
<td>9%</td>
<td>0.4</td>
</tr>
<tr>
<td>35</td>
<td>Not Contacted</td>
<td>0</td>
</tr>
</tbody>
</table>

Source: Modified by Advanced Resources, based on data from Wasson Denver Unit CO2 flood observation pilot (Goodyear and Jensen, 2011).
“Poster Child” for Integrating CO$_2$-EOR and CO$_2$ Storage

- Largest CO$_2$ EOR project in Canada:
  - OOIP 1.4 Bbbls
  - 200 MMB incremental oil from CO$_2$-EOR

- World’s largest geological CO$_2$ storage project:
  - 2.4 MMt/year (current)
  - 24 MMt to date

- A 200 mile CO$_2$ pipeline connects the Coal Gasification Plant at Beulah, ND with the Weyburn oil field in Canada.

Source: EnCana, 2005
Permian Basin ROZ Below Existing Oil Fields

Oil Saturation Profile in the TZ/ROZ (Wasson Denver Unit Well Log)

Wasson Denver Unit Oil Resources (Billion Barrels)

<table>
<thead>
<tr>
<th></th>
<th>Main Pay Zone</th>
<th>TZ/ROZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>OOIP</td>
<td>2.4</td>
<td>3.0</td>
</tr>
<tr>
<td>P/S Recovery</td>
<td>1.1</td>
<td>1.5*</td>
</tr>
<tr>
<td>“Stranded”</td>
<td>1.3</td>
<td>1.5</td>
</tr>
<tr>
<td>EOR Potential</td>
<td>0.5**</td>
<td>0.5***</td>
</tr>
</tbody>
</table>

*Produced by nature. **Approximately 0.3 billion barrels already produced/proven to date. ***Numerous ROZ projects underway.

Seminole Unit (San Andres) ROZ Project
(Three Hess Oil operated miscible CO₂ floods in the ROZ interval show successful oil response.)

<table>
<thead>
<tr>
<th>Project</th>
<th>Acres</th>
<th>CO₂ Injection Patterns</th>
<th>Oil Production (B/D)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>2010</td>
</tr>
<tr>
<td>Phase 1</td>
<td>500</td>
<td>10</td>
<td>1,200</td>
</tr>
<tr>
<td>Phase 2</td>
<td>480</td>
<td>9</td>
<td>1,700</td>
</tr>
<tr>
<td>Stage 1</td>
<td>2,320</td>
<td>29</td>
<td>1,000</td>
</tr>
</tbody>
</table>
ARI and Melzer estimate that up to 100 million barrels of OIP exist in the ROZ “Fairways” of the Permian Basin.
Deployment of CO$_2$-EOR in Offshore Oil Fields

In 2005, Advanced Resources took a “first look” at the CO$_2$-EOR potential of oil fields located in the shallow-water shelf of offshore Louisiana. Since then, a number of efforts have been undertaken to bring offshore CO$_2$-EOR closer to reality:

- In mid-2012, Scotland established CENSOR-CO$_2$ - Center for North Sea Enhanced Oil Recovery with CO$_2$ - to “unlock 3 billion barrels of oil from the North Sea.”
- In a recent SPE paper, Shell discusses efforts “to implement new generation CO$_2$ projects, including offshore application.”
2. To What Extent Can CO₂-EOR Provide Carbon Neutral Energy?

At 1 metric ton of CO₂ injected per 2.5 barrels of oil recovered, the carbon balance of CO₂-EOR is close to neutral, when using otherwise vented CO₂.

With a gravity stable process, CO₂-EOR can store more CO₂ than the carbon content of the oil (“green oil”).
Opposition to Storing CO$_2$ with EOR Seems Misplaced

A number of activities besides CO$_2$-EOR bring additional oil to the surface, including exploration and drilling for conventional oil.

Except in environmentally fragile areas, no public official concerned with energy security and economic well-being has called for a stop to conventional oil exploration or production.

Norway’s Statoil announced a goal of 60% recovery from its offshore oilfields. This announcement was meet with praise not protest.

CO$_2$-EOR is much more carbon-neutral than conventional oil exploration or Norway’s actions on conservation of its oil resources.
3. What is the “Size of the Prize?”

Large volumes of oil remain “stranded” in U.S. reservoirs after traditional recovery.

400 BILLION BARRELS OF OIL IN MAIN PAY ZONES.

Original Oil In-Place: 600 B Barrels

“Stranded” Oil In-Place: 396 B Barrels

Target for EOR
396 Billion Barrels

Cumulative Production
182 Billion Barrels

Proved Reserves
22 Billion Barrels

140 BILLION BARRELS OF OIL IN RESIDUAL OIL ZONES (ROZs).

Oil In-Place: 140 B Barrels*

ROZ “Fairways”
100 Billion Barrels

Below Oil Fields

40 Billion Barrels

*Within ROZ “Fairways” of the Permian Basin and below oil fields in 3 U.S. basins

Source: Advanced Resources Int’l. (2011); Melzer Consulting (2012)
Oil Recovery and CO$_2$ Demand/Storage: “Next Generation” CO$_2$-EOR Technology

Two publically available reports, prepared by Advanced Resources Int’l and Melzer Consulting for U.S. DOE/NETL, provide the analytical foundation for the estimates of oil production and CO$_2$ demand by the CO$_2$-EOR industry.
The Size of the Prize

- In the U.S., the “size of the oil prize” for “next generation” CO₂-EOR technology is 100 billion barrels of economically recoverable oil,* nearly four times larger than from today’s “state of the art” CO₂-EOR technology and practices.

- The economic demand for CO₂ from “next generation” CO₂-EOR is 33 billion metric tons. Subtracting 3 billion metric tons of natural CO₂, the “size of the CO₂ utilization and storage prize” in the U.S. is 30 billion metric tons.

- This is equal to 35 years of CO₂ emissions captured from 140 GWs of coal-fired power.

*Using an oil price of $85 per barrel,* a CO₂ price of $40 per metric ton, and a return on investment hurdle of 20%. All economic value numbers are expressed in U.S. dollars.
Impact of Applying “Next Generation” vs. SOA CO₂-EOR Technology to U.S. Oil Fields and ROZ

<table>
<thead>
<tr>
<th>Resource Area</th>
<th>Economic Oil Recovery (BBbls)*</th>
<th>Demand for CO₂ (Billion Metric Tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SOA</td>
<td>Next Gen.</td>
</tr>
<tr>
<td>More efficient recovery, “Lower 48” oil fields</td>
<td>24</td>
<td>60</td>
</tr>
<tr>
<td>Alaska/Offshore</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>Residual Oil Zone (below oil fields)</td>
<td>-</td>
<td>13</td>
</tr>
<tr>
<td>Residual Oil Zone “Fairways” (preliminary)</td>
<td>-</td>
<td>20</td>
</tr>
<tr>
<td>Total</td>
<td>27</td>
<td>100</td>
</tr>
</tbody>
</table>

*At $85 per barrel and $40 per metric ton, CO₂ market price with 20% rate of return (before tax).
Source: Advanced Resources International, Inc. (2011)
4. To What Extent Could CO$_2$-EOR Provide A Market-Driven Option for CO$_2$ Capture?

“Next generation” CO$_2$-EOR technology would generate gross domestic production (GDP) of $8.5 trillion, over the next thirty to forty years.

As part of this, the U.S. CO$_2$-EOR industry could provide:

- Revenues of $1.3 trillion for CO$_2$, with 90% for CO$_2$ capture.
- About $2.1 trillion of severance and income taxes.
- About $2.3 trillion of demand for services and materials.

Over 30 billion metric tons of anthropogenic CO$_2$, otherwise vented to atmosphere, would be permanently stored.
The “Value Chain” of “Next Generation” CO$_2$-EOR

<table>
<thead>
<tr>
<th>Revenue Recipient</th>
<th>Value Chain Function</th>
<th>Revenues Per Barrel ($)</th>
<th>TOTAL* ($ billion)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power/Industrial Companies</td>
<td>Sale of CO$_2$</td>
<td>$13.20</td>
<td>$1,320**</td>
</tr>
<tr>
<td>Federal/State Treasuries</td>
<td>Severance/Income Taxes</td>
<td>$21.30</td>
<td>$2,130</td>
</tr>
<tr>
<td>U.S. Economy</td>
<td>Services, Materials and Sales</td>
<td>$23.00</td>
<td>$2,300</td>
</tr>
<tr>
<td>Other</td>
<td>Private Mineral Rights</td>
<td>$7.70</td>
<td>$770</td>
</tr>
<tr>
<td>Oil Industry</td>
<td>Return of/on Capital</td>
<td>$19.80</td>
<td>$1,980</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>$85.00</td>
<td>$8,500</td>
</tr>
</tbody>
</table>

*Assuming 100 billion barrels of economically feasible oil recovery; oil prices of $85 per barrel and CO$_2$ sales price of $40/metric tons.

**Of the 33 billion metric ton, $1,320 billion overall market for CO$_2$, anthropogenic CO$_2$ captured from power and other industrial plants would be 30 billion metric tons and $1,200 billion.

Source: Advanced Resources International, Inc. (2011)
### Distribution of Economic Value of Oil Production from CO₂-EOR

<table>
<thead>
<tr>
<th>Notes</th>
<th>EOR Industry</th>
<th>Federal/State</th>
<th>Power Plant/Other</th>
<th>Private Royalties</th>
<th>U.S. Economy</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Domestic Oil Price ($/B)</td>
<td>$85.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Less: Royalties</td>
<td>($14.90)</td>
<td>$2.50</td>
<td>$12.40</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Production Taxes</td>
<td>($3.50)</td>
<td>$4.10</td>
<td>($0.60)</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>CO₂ Purchase Costs</td>
<td>($13.20)</td>
<td></td>
<td>$13.20</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>CO₂ Recycle Costs</td>
<td>($6.00)</td>
<td></td>
<td>($6.00)</td>
<td>$6.00</td>
</tr>
<tr>
<td>6</td>
<td>O&amp;M/G&amp;A Costs</td>
<td>($10.00)</td>
<td></td>
<td>($10.00)</td>
<td>$10.00</td>
</tr>
<tr>
<td>7</td>
<td>CAPEX</td>
<td>($7.00)</td>
<td></td>
<td>$7.00</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Total Costs</td>
<td>($54.60)</td>
<td></td>
<td></td>
<td>$7.00</td>
</tr>
</tbody>
</table>

#### Notes:
- (1.) Assumes $85 per barrel of oil;
- (2.) Royalties are 17.5%; 1 of 6 barrels produced are from federal and state lands;
- (3.) Production and ad valorem taxes of 5%, from FRS data;
- (4.) CO₂ market price of $40/tonne, including transport; 0.33 tonnes of purchased CO₂ per barrel of oil; CCS meets 90% of CO₂ demand;
- (5.) CO₂ recycle cost of $10/tonne; 0.6 tonnes of recycled CO₂ per barrel of oil;
- (6.) O&M/G&A costs from ARI CO₂-EOR cost models;
- (7.) CAPEX from ARI CO₂-EOR cost models;
- (8.) Combined Federal and state income taxes of 35%, from FRS data.
Advanced Power Plants Plan to Use EOR for CO\(_2\) Storage

**Southern Company’s Kemper County IGCC Plant**
- 582 MW fueled by Mississippi Lignite
- Will Capture 65% of CO\(_2\)
- Negotiating agreement to sell 1.1 to 1.5 million tons of CO\(_2\) per year for EOR (170-225 MMcfd)
- Project expected to cost $2.4 B and be operational by 2014.

**Summit’s Texas Clean Energy IGCC Project**
- 400 MW IGCC with 90% capture
- Located near Odessa in Permian Basin
- Sell 2.5 million tons of CO\(_2\) per year to EOR market
- Expected cost $1.75 B; $350 MM award under CCPI Round 3.

*Source: Mississippi Power, Denbury Resources
Source: Siemens Energy*
Summary Observations

“Next generation” CO₂ enhanced oil recovery deserves to be a major part of a worldwide carbon management strategy:

- CO₂ enhanced oil recovery is a viable, growing enterprise,
- The oil produced is low carbon energy,
- The “size of the prize” is large, and
- CO₂-EOR can provide a market-driven option for accelerating CO₂ capture.

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