The Economics of CO$_2$ Sequestration through Enhanced Oil Recovery

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(co-authored with Klaas van ’t Veld, University of Wyoming, and Andrew Leach, University of Alberta)
- Enhanced Oil Recovery (EOR) is the process of injecting CO\textsubscript{2} into mature oil fields to encourage increased production
  - typically undertaken after secondary production (water flood)
  - hence called tertiary production
- CO\textsubscript{2} mixes with oil, raising pressure and lowering viscosity
- so oil flows to well bore more efficiently, resultant production is mix of oil, water and CO\textsubscript{2}
- process involves combination of incremental purchases of CO\textsubscript{2} and recycled CO\textsubscript{2}
- CO\textsubscript{2} replaces oil in pore space — resulting in carbon sequestration
- many examples in US (mainly Texas and Wyoming), also some in Europe
CO$_2$-EOR Flows
CO$_2$-EOR Flows

\[ q_{\text{inj}} \]

\[ q_{\text{wat}} \]

\[ q_{\text{CO}_2} \]
CO$_2$-EOR Flows

$q_{\text{inj}}^{\text{inj}}$ $q_{\text{CO}_2}^{\text{inj}}$ $q_{\text{wat}}^{\text{inj}}$ $q_{\text{prd}}^{\text{inj}}$
CO$_2$-EOR Flows

$q_{\text{inj}}^{\text{CO}_2}$

$q_{\text{prd}}^{\text{oil}}$
CO$_2$-EOR Flows

\[ q_{\text{inj}}^{\text{CO}_2} \rightarrow q_{\text{CO}_2}^{\text{rec}} \leftarrow q_{\text{CO}_2}^{\text{rec}} \rightarrow q_{\text{oil}}^{\text{prd}} \]
CO$_2$-EOR Flows

$q^{\text{inj}}$ \( q_{\text{CO2}} \) \( q^{\text{rec}}_{\text{CO2}} \) \( q^{\text{rec}}_{\text{CO2}} \) \( q_{\text{oil}}^{\text{prd}} \)
CO$_2$-EOR Flows

\[ q^{\text{inj}}_{\text{CO}_2} \rightarrow q^{\text{rec}}_{\text{CO}_2} \rightarrow q^{\text{prd}}_{\text{oil}} \]
\( q_{\text{inj}}^{\text{CO}_2} \downarrow \quad q_{\text{rec}}^{\text{CO}_2} \quad \uparrow \quad q_{\text{seq}}^{\text{CO}_2} \quad \rightarrow \quad q_{\text{pur}}^{\text{CO}_2} \quad \rightarrow \quad q_{\text{prd}}^{\text{oil}} \)
CO\textsubscript{2}-EOR Flows

\[ q^{\text{pur}}_{\text{CO}_2} = q^{\text{seq}}_{\text{CO}_2} \]
CO$_2$-EOR Flows

$q^{pur}_{CO2}$ → $q^{rec}_{CO2}$ → $q^{seq}_{CO2}$ → $q^{pur}_{CO2}$

$q^{rec}_{CO2}$ ← $q^{rec}_{CO2}$ ← $q^{rec}_{CO2}$ ← $q^{rec}_{CO2}$

$q^{inj}_{CO2}$ ↓ $q^{inj}_{CO2}$ ↓ $q^{inj}_{CO2}$ ↓ $q^{inj}_{CO2}$ ↓

$q^{prd}_{oil}$ → $q^{prd}_{oil}$ → $q^{prd}_{oil}$ → $q^{prd}_{oil}$ →
$q^{\text{rec}}_{\text{CO}_2} = q^{\text{inj}}_{\text{CO}_2} - q^{\text{seq}}_{\text{CO}_2}$
**Profit objective function**

\[
\text{profit} = \underbrace{p_{\text{oil}} q_{\text{oil}}^\text{prd}}_{\text{oil revenues}} - \underbrace{p_{\text{CO}_2} q_{\text{CO}_2}^\text{pur}}_{\text{CO}_2 \text{ purchase costs}} - \underbrace{c_{\text{rec}} q_{\text{CO}_2}^\text{rec}}_{\text{CO}_2 \text{ recycling costs}} - \underbrace{c_{\text{oth}}}_{\text{other costs}}
\]
Profit objective function

\[
\text{profit} = p_{\text{oil}} q_{\text{oil}}^{\text{prd}} + s_{\text{CO}_2} q_{\text{CO}_2}^{\text{seq}} - p_{\text{CO}_2} q_{\text{CO}_2}^{\text{pur}} - c_{\text{rec}} q_{\text{CO}_2}^{\text{rec}} - c_{\text{oth}}
\]
Profit objective function

\[
\begin{align*}
\text{profit} &= p_{oil} q_{oil}^{\text{prd}} + s_{CO_2} q_{CO_2}^{\text{seq}} - p_{CO_2} q_{CO_2}^{\text{pur}} - c_{\text{rec}} q_{CO_2}^{\text{rec}} - c_{\text{oth}}
\end{align*}
\]
**Profit objective function**

\[
\text{profit} = \underbrace{p_{\text{oil}} q_{\text{oil}}^{\text{prod}}}_{\text{oil revenues}} + \underbrace{(s_{\text{CO}_2} - p_{\text{CO}_2}) q_{\text{CO}_2}^{\text{seq}}}_{\text{net CO}_2 \text{ sequestration revenues}} - \underbrace{c^{\text{rec}} q_{\text{CO}_2}^{\text{rec}}}_{\text{CO}_2 \text{ recycling costs}} - \underbrace{c^{\text{oth}}}_{\text{other costs}}
\]
Profit objective function

\[ q_{CO_2}^{rec} = q_{CO_2}^{inj} - q_{CO_2}^{seq} \]

\[ \text{profit} = \underbrace{p_{oil} q_{oil}^{prd}}_{\text{oil revenues}} + \underbrace{(s_{CO_2} - p_{CO_2}) q_{CO_2}^{seq}}_{\text{net CO}_2 \text{ sequestration revenues}} - \underbrace{c_{rec} q_{CO_2}^{rec}}_{\text{CO}_2 \text{ recycling costs}} - \underbrace{c_{oth}}_{\text{other costs}} \]
Profit objective function

\[
\text{profit} = p_{\text{oil}} q_{\text{oil}}^{\text{prd}} + (s_{\text{CO}_2} - p_{\text{CO}_2} + c_{\text{rec}}) q_{\text{CO}_2}^{\text{seq}} - c_{\text{rec}} q_{\text{CO}_2}^{\text{inj}} - c_{\text{oth}}
\]
Profit objective function

\[
profit = p_{oil} q_{oil}^{prd} + (s_{CO_2} - p_{CO_2} + c^{rec}) q_{CO_2}^{seq} - c^{rec} q_{CO_2}^{inj} - c^{oth}
\]

- weight on oil production
- weight on CO₂ sequestration
- gross CO₂ recycling costs
- other costs
Problem: ad hoc engineering assumptions

**Assumption 1:** Oil production is an inverse U-shaped function of the CO$_2$ injection fraction $q_{\text{CO}_2}^{\text{inj}}/(q_{\text{CO}_2}^{\text{inj}} + q_{\text{wat}}^{\text{inj}})$.
Flow rates as function of CO2 injection fraction

Rates (fraction of remaining reserves/year) vs. CO2 injection fraction

- **Oil production**
**Problem: ad hoc engineering assumptions**

**Assumption 1:** Oil production is an inverse U-shaped function of the CO₂ injection fraction \( q_{\text{inj}}^{\text{CO}_2} \left/ \left( q_{\text{CO}_2}^{\text{inj}} + q_{\text{wat}}^{\text{inj}} \right) \right. \).

**Assumption 2:** CO₂ sequestration is the product of the CO₂ injection fraction and oil production:

\[
q_{\text{seq}}^{\text{CO}_2} = \left( q_{\text{inj}}^{\text{CO}_2} \left/ \left( q_{\text{CO}_2}^{\text{inj}} + q_{\text{wat}}^{\text{inj}} \right) \right. \right) \times q_{\text{oil}}^{\text{prd}}
\]
Flow rates as function of CO2 injection fraction

- **Oil production**
- **CO2 sequestration**

<table>
<thead>
<tr>
<th>CO2 injection fraction</th>
<th>Rates (fraction of remaining reserves/year)</th>
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<tbody>
<tr>
<td>0</td>
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Annual Per-Field CO₂ Injection Rates by Year

Profit objective function

\[
\text{profit} = \underbrace{p_{\text{oil}} q_{\text{oil}}^{\text{prd}}}_{\text{weight on oil production}} + \underbrace{(s_{\text{CO}_2} - p_{\text{CO}_2} + c_{\text{rec}})}_{\text{weight on CO}_2 \text{ sequestration}} \underbrace{q_{\text{CO}_2}^{\text{seq}}}_{\text{weight on CO}_2 \text{ sequestration}} - \underbrace{c_{\text{rec}} q_{\text{CO}_2}^{\text{inj}}}_{\text{weight on CO}_2 \text{ recycling}} - \underbrace{c_{\text{oth}}}_{\text{other costs}}
\]

Benefits of CO\(_2\) injection fall over time

Costs must fall over time
Flow CO2 injection

Rate (million bl/year) vs. Time (years)

- $50/bl
Flow CO₂ injection

- p $50/bl
- p $100/bl

Rate (million bl/year) vs Time (years)
Flow CO2 injection

- $50/bl
- $100/bl
- $150/bl
Flow CO2 injection

- $50/\text{bl}$
- $100/\text{bl}$
- $150/\text{bl}$
- $200/\text{bl}$
Cumulative CO2 sequestration
Cumulative CO$_2$ sequestration

Time (years)

Quantity (million bl)

- p $50/bl
- p $100/bl
Cumulative CO2 sequestration

- $p$ $50/\text{bl}$
- $p$ $100/\text{bl}$
- $p$ $150/\text{bl}$

Time (years)

Quantity (million bl)
Cumulative CO2 sequestration

- $50/bl
- $100/bl
- $150/bl
- $200/bl

Quantity (million bl) vs. Time (years)
Flow oil production

- Blue line: waterflood
- Gray line: p $50/bl

Time (years) vs. Rate (million bl/year)
Flow oil production

- **Rate (million bl/year)**
- **Time (years)**

**Legend:**
- **waterflood**
- $\text{p $50/bl}$
- $\text{p $100/bl}$
Flow oil production

Rate (million bbl/year) vs. Time (years)

- Waterflood
- $50/\text{bl}$
- $100/\text{bl}$
- $150/\text{bl}$

Effect of oil prices and CO$_2$-storage subsidies

Optimal policy
Flow oil production

- Waterflood
- p $50/bl
- p $100/bl
- p $150/bl
- p $200/bl

Time (years)
Rate (million bl/year)
Cumulative oil production

- Blue line: Waterflood
- Dark gray line: p $50/bl
- Light gray line: p $100/bl

Time (years) vs. Quantity (million bl)
Cumulative oil production

- Waterflood
- $p = $50/bl
- $p = $100/bl
- $p = $150/bl

Cumulative oil production as a function of time for different oil prices and storage subsidies.
Cumulative oil production

Time (years)

Quantity (million bl)

- $50/bl
- $100/bl
- $150/bl
- $200/bl

Legend:
- blue: waterflood
- grey: $50/bl
- grey: $100/bl
- black: $150/bl
- black: $200/bl
Flow CO2 injection

Rate (million bl/year)

Time (years)

subsidy $0/tCO2
Effect of oil prices and CO₂-storage subsidies

**Flow CO₂ injection**

- subsidy $0/\text{tCO}_2$
- subsidy $40/\text{tCO}_2$

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Common misconception

Optimal policy

Engineering studies

Economic study
Flow CO2 injection

- Subsidy $0/tCO2
- Subsidy $40/tCO2
- Subsidy $80/tCO2

Rate (million bl/year)

Time (years)
Flow CO2 injection

- subsidy $0/tCO2
- subsidy $40/tCO2
- subsidy $80/tCO2
- subsidy $120/tCO2

Rate (million bl/year) vs. Time (years)
Cumulative CO2 sequestration

Time (years) vs Quantity (million bl)

- For a subsidy of $0/tCO2, the cumulative CO2 sequestration reaches a steady state after approximately 20 years, with a maximum value of around 0.35 million barrels.
Cumulative CO2 sequestration

Time (years)

Quantity (million bl)

- Subsidy $0/tCO2
- Subsidy $40/tCO2
Cumulative CO2 sequestration

- Subsidy $0/tCO2
- Subsidy $40/tCO2
- Subsidy $80/tCO2

Quantity (million bl)

Time (years)
Effect of oil prices and CO$_2$-storage subsidies

Common misconception

Optimal policy

Cumulative CO2 sequestration

- Subsidy $0/tCO2
- Subsidy $40/tCO2
- Subsidy $80/tCO2
- Subsidy $120/tCO2

Time (years)

Quantity (million bl)
Flow oil production

- Blue line: waterflood
- Gray line: subsidy $0/tCO2

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Common misconception:
- Optimal policy
- Economic study
- Effect of oil prices and CO2-storage subsidies
- Engineering studies
Flow oil production

- Waterflood
- Subsidy $0/tCO2
- Subsidy $40/tCO2

Rate (million bl/year) vs. Time (years)
Flow oil production

- Waterflood
- Subsidy $0/tCO2
- Subsidy $40/tCO2
- Subsidy $80/tCO2

Rate (million bl/year) vs Time (years)
Flow oil production

- Waterflood
- Subsidy $0/tCO2
- Subsidy $40/tCO2
- Subsidy $80/tCO2
- Subsidy $120/tCO2

Rate (million bl/year) vs. Time (years)
Cumulative oil production

Time (years)

Quantity (million bl)

- Waterflood
- Subsidy $0/\text{tCO}_2$
Effect of oil prices and CO$_2$-storage subsidies

Cumulative oil production

- Waterflood
- Subsidy $0$/tCO$_2$
- Subsidy $40$/tCO$_2$
- Subsidy $80$/tCO$_2$
Cumulative oil production

- Waterflood
- Subsidy $0/tCO2
- Subsidy $40/tCO2
- Subsidy $80/tCO2
- Subsidy $120/tCO2

Time (years)

Quantity (million bl)
Effect of oil prices and CO$_2$-storage subsidies

**CO$_2$-EOR profits**

\[ NPV = \underbrace{p_{\text{oil}}}_{\text{weight on oil production}} \cdot Q_{\text{oil}}^{\text{prd}} + \underbrace{(s_{\text{CO}_2} - p_{\text{CO}_2} + c^{\text{rec}})}_{\text{weight on CO}_2 \text{ sequestration}} \cdot Q_{\text{CO}_2}^{\text{seq}} - \underbrace{c^{\text{rec}} \cdot Q_{\text{CO}_2}^{\text{inj}}}_{\text{weight on CO}_2 \text{ recycling}} - \underbrace{C^{\text{oth}}}_{\text{other costs}} \]

\[ \approx \$100 \rightarrow \$200 \]
\[ NPV = p_{oil} Q_{oil}^{\text{prd}} + (s_{CO_2} - p_{CO_2} + c_{\text{rec}}) Q_{CO_2}^{\text{seq}} - c_{\text{rec}} Q_{CO_2}^{\text{inj}} - c_{\text{oth}} \]

- Weight on oil production: \( p_{oil} \)
- Weight on oil production: \( Q_{oil}^{\text{prd}} \)
- Weight on CO\(_2\) sequestration: \( s_{CO_2} - p_{CO_2} + c_{\text{rec}} \)
- Weight on CO\(_2\) recycling: \( c_{\text{rec}} \)
- Weight on CO\(_2\) injection: \( Q_{CO_2}^{\text{inj}} \)
- Other costs: \( c_{\text{oth}} \)

\( \approx \$100 \rightarrow \$200 \)
\( \approx \$1 \rightarrow \$5 \)
Flow rates as function of CO2 injection fraction

- **Oil production**
- **CO2 sequestration**

Rates (fraction of remaining reserves/year)

CO2 injection fraction
So . . .

. . . are high oil prices the environmentalist’s best friend?

- On the demand side: discourage oil use
- On the supply side: promote CO$_2$ storage through EOR

Not necessarily, for two reasons:
So . . .

. . . are high oil prices the environmentalist’s best friend?

- On the demand side: discourage oil use
- On the supply side: promote CO$_2$ storage through EOR

Not necessarily, for two reasons:

- *Increasing* oil prices may *reduce* CO$_2$ storage through EOR
CO$_2$-EOR profits

\[ NPV = - \left( I - \text{up-front investment cost} \right) \]

\[ = p_{oil} Q_{oil}^{\text{prd}} + (s_{CO_2} - p_{CO_2} + c_{\text{rec}}) Q_{CO_2}^{\text{seq}} - c_{\text{rec}} Q_{CO_2}^{\text{inj}} - c_{\text{oth}} \]

- Weight on oil production
- Weight on CO$_2$ sequestration
- Weight on CO$_2$ recycling
- Other costs
$NPV = - \sum I_{\text{up-front investment cost}} + p_{\text{oil}} Q_{\text{oil}}^{\text{prod}} + \left(s_{\text{CO}_2} - p_{\text{CO}_2} + c_{\text{rec}}\right) Q_{\text{CO}_2}^{\text{seq}} - c_{\text{rec}} Q_{\text{CO}_2}^{\text{inj}} - C_{\text{oth}}$
Flow CO2 injection

- $p$ growth 0%
- $p$ growth 2.5%

Rate (million bl/year) vs. Time (years)
Flow CO2 injection

- p growth 0%
- p growth 2.5%
- p growth 5%

Rate (million bl/year) vs. Time (years)

- Flow CO2 injection graph showing the effect of oil prices and CO2 storage subsidies.
Flow oil production

- Waterflood
- p growth 0%

Rate (million bbl/year) vs. Time (years)
Flow oil production

- Waterflood
- p growth 0%
- p growth 2.5%

Rate (million bbl/year) vs. Time (years)
Cumulative CO2 sequestration

Time (years) vs. Quantity (million bl)

- **Cumulative CO2 sequestration**

  - **Y-axis**: Quantity (million bl)
  - **X-axis**: Time (years)

  - The graph shows the cumulative CO2 sequestration over time.
  - The growth is depicted on a scale from 0 to 0.35 on the y-axis.
  - The x-axis ranges from 0 to 45 years.

  - The graph is labeled with "p growth 0%".
Cumulative CO2 sequestration

- **p growth 0%**
- **p growth 2.5%**

- **Time (years)**
- **Quantity (million bl)**

![Graph showing cumulative CO2 sequestration with two lines representing different growth rates.](image-url)
Cumulative CO2 sequestration

- p growth 0%
- p growth 2.5%
- p growth 5%

Time (years)

Quantity (million bl)
Cumulative CO2 sequestration

- p growth 0%
- p growth 2.5%
- p growth 5%
- p growth 7.5%
So . . .

. . . are high oil prices the environmentalist’s best friend?

- On the demand side: discourage oil use
- On the supply side: promote CO₂ storage through EOR

Not necessarily, for two reasons:

- *Increasing* oil prices may *reduce* CO₂ storage through EOR
- Promoting CO₂-EOR may increase *net* CO₂ emissions
Emissions from incremental oil produced with CO$_2$-EOR don’t matter.

“\textit{World oil production is determined by world oil demand and if CO$_2$-EOR projects were not undertaken, some other source of oil would step forward and fill the gap. Therefore, executing CO$_2$-EOR projects will not result in incremental aggregate refining and consumption emissions.}”

Oil market

$p_{oil}$ vs. $Q_{oil}$

$p^*$

Demand

Supply

$p^*$ vs. $Q^*$

Optimal policy
Oil market

Demand

Supply

Conventional

EOR

$Q^*$

$Q_{oil}$

$p_{oil}$

$p^*$

$p^{**}$

$p^*$

Common misconception

Effect of oil prices and CO$_2$-storage subsidies

Optimal policy

Conventional

Engineering studies

Economic study
Oil market

\[ p_{\text{oil}} \]

\[ Q_{\text{oil}} \]

\[ p^* \]

\[ Q^* \]
Oil market

$p_{oil}$

$p^*$

$p^{**}$

Supply

Demand

$Q^*$

$Q^{**}$

$Q_{oil}$
Oil market

$p_{oil}$

$Q_{oil}$

$Q^*$ $Q^{**}$

$p^*$ $p^{**}$

Conventional

EOR
Figure 7. Oil-price and oil-production paths with and without CO\(_2\)-EOR, when the price of the backstop technology is either constant (panels (a) and (b)) or falling over time (panels (c) and (d)).

Importantly, because the backstop price is constant, all conventional projects that are economic without the introduction of EOR eventually become economic also when EOR is introduced. As a result, the accumulated amount of oil produced from conventional sources is unaffected (i.e., the areas under the oil-quantity paths \(Q_{\text{con}}\) and \(Q_{\text{con+EOR}}\) are identical). In other words, EOR production ultimately displaces no conventional oil production at all.
Figure 7. Oil-price and oil-production paths with and without CO\(_2\)-EOR, when the price of the backstop technology is either constant (panels (a) and (b)) or falling over time (panels (c) and (d)).

Over time, \(T_{\text{con}} = 4\), whereas \(T_{\text{con}+\text{EOR}} = 8\). Importantly, because the backstop price is constant, all conventional projects that are economic without the introduction of EOR eventually become economic also when EOR is introduced. As a result, the accumulated amount of oil produced from conventional sources is unaffected (i.e., the areas under the oil-quantity paths \(Q_{\text{con}}\) and \(Q_{\text{con}+\text{EOR}}\) are identical). In other words, EOR production ultimately displaces no conventional oil production at all.
Common misconception

- So displacement of conventional oil is not one-for-one
- Moreover, conventional oil is also “displaced” by ...
  - wind
  - solar
  - ethanol
  - nuclear

- Does that make their net CO$_2$ emissions *negative*?
- But if some CO$_2$-EOR projects generate positive net emissions, while others generate negative net emissions, what then is the optimal way of promoting EOR?

- Do we need taxes for some, and subsidies for others?
Common misconception

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- Do we need taxes for some, and subsidies for others?
- No, the optimal policy to promote CO₂-EOR is quite simply
  - *tax on CO₂ emissions* (equal to the per-unit emission damages)
Common misconception

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- Do we need taxes for some, and subsidies for others?
- No, the optimal policy to promote CO$_2$-EOR is quite simply 
  - tax on CO$_2$ emissions (equal to the per-unit emission damages) 
    which for CO$_2$-EOR producers acts exactly like 
  - a subsidy on CO$_2$ sequestration (i.e., on avoided CO$_2$ emissions)