CO₂ mitigation:
- EOR (emissions verification and liability)
- Industrial (petrochem, food processing, etc)
- Sequestration (brines, other)

“Finding” cost
- CO₂ from field production (associated, non-associated)
- CO₂ from petrochem
- CO₂ from power production

“Market” (includes bilateral contracts)

Cost of captured CO₂ vs. natural CO₂ production
- Cost of transportation (feasibility, ROW, potential for conversion of existing ROW)
- Storage to mitigate interruptible CO₂ supply, demand (3rd party disposal for excess CO₂)
- Basis – produced vs. captured, distance from capture to injection
- Forward market for risk management
- Carbon credit system (if needed)
- Insurance, verification

Re-capture of CO₂ from refining point sources (development of “closed loop” for petroleum)

Facilitating Commercial Frameworks (policy, regulatory, financial)

Title Transfer

Aug 15 clarifications
Potential for competing processes
Integrated CO2-EOR Project Economics

Cost Models

- Capture cost = \( f(\text{amount of CO}_2, \text{utility costs, concentration, pressure, stability, etc.}) \)
- Storage cost = \( f(\text{capacity, materials, compression, liquefaction, etc.}) \)
- Transport cost = \( f(\text{diameter, length, compression, etc.}) \)
- EOR cost = \( f(\text{CO}_2 \text{ effectiveness, recycle ratio, injection, depth, etc.}) \)

DCF model

Some preliminary numbers

<table>
<thead>
<tr>
<th></th>
<th>Cost of CCS ($/bbl)</th>
<th>Cost of Oil Production ($/bbl)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Capture</td>
<td>Transport*</td>
</tr>
<tr>
<td>Low</td>
<td>6.67</td>
<td>0.13</td>
</tr>
<tr>
<td>Medium</td>
<td>15.00</td>
<td>0.60</td>
</tr>
<tr>
<td>High</td>
<td>23.33</td>
<td>1.07</td>
</tr>
</tbody>
</table>

Sources: IPCC for CCS, EPRI for EOR costs
## Some preliminary numbers II

### Cost of CCS ($/bbl) vs. Cost of Oil Production ($/bbl)

<table>
<thead>
<tr>
<th></th>
<th>Capture</th>
<th>Transport*</th>
<th>Storage†</th>
<th>Total</th>
<th>O&amp;M</th>
<th>EOR</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>2</td>
<td>0.47</td>
<td>0.33</td>
<td>2.80</td>
<td>5</td>
<td>3.5</td>
<td>8.5</td>
</tr>
<tr>
<td>Medium</td>
<td>12</td>
<td>1.40</td>
<td>2.83</td>
<td>16.23</td>
<td>10</td>
<td>4</td>
<td>14</td>
</tr>
<tr>
<td>High</td>
<td>22</td>
<td>2.33</td>
<td>5.33</td>
<td>29.67</td>
<td>15</td>
<td>4.5</td>
<td>19.5</td>
</tr>
</tbody>
</table>

Sources: *Can Geological Carbon Storage Be Competitive?* Steffen Kallbekken & Asbjørn Torvanger, Center for International Climate and Environmental Research (CICERO), Norway, May 2004 for CCS, and EPRI for EOR costs.

### Integrated CO2-EOR Project Economics, II (Aug 15)

**Policy approaches drive scenarios**

- CO2 mitigation NPV>0 w/ higher oil price
- CO2 is a waste (designation as hazardous waste?)
- CO2 mitigation NPV>0 w/ credit/offset
- CO2 is a commodity
Selection Process - Oil Fields

- Short listed first 31 large oil fields (NOTE from Aug 15 – where can units be formed? Can units be formed at the most prospective fields?)
  - Starting with Conroe in Montgomery County
    - Cumulative production to date -710 mmSTB
    - Oil recoverable through EOR – 213 mmSTB
    - CO2 required for EOR – 28 million tons
    - Storage potential after EOR – 78 million tons
  - Ending with Refugio-Fox in Refugio County
    - Cumulative production to date - 44 mmSTB
    - Oil recoverable through EOR – ~13 mmSTB
    - CO2 required for EOR – ~2 million tons
    - Storage potential after EOR – ~4 million tons

---

Selected oil fields

<table>
<thead>
<tr>
<th></th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total recoverable oil recoverable in billion stock barrels (STB)</td>
<td>1.48</td>
<td>1.51</td>
</tr>
<tr>
<td>CO2 required for EOR in million tons</td>
<td>191</td>
<td>196</td>
</tr>
<tr>
<td>Total oil field CO2 storage potential after EOR in</td>
<td>615</td>
<td>635</td>
</tr>
<tr>
<td>Total CO2 required for both EOR and storage after EOR</td>
<td>806</td>
<td>831</td>
</tr>
<tr>
<td>Annual CO2 required for EOR and sequestration assuming a 20 yr economic operation of a capture technology</td>
<td>40 – 42 million tons</td>
<td></td>
</tr>
</tbody>
</table>
Selection process – CO₂ sources

- Limited selection only to power plants located in the Gulf Coast Region
- Potential CO₂ supply -
  - 131 million tons annually when gas plants operate at average Capacity factors (less than 50% CF) as today
  - 190 million tons annually when gas plants operate at their optimal average Capacity factors (above 70% CF).
  - Coal power plants alone: 212 million tons annually
- CO₂ Demand for EOR and sequestration
  - Total: 796 million tons
  - Annual: 40 million tons/yr for 20 years
- Excess supply: 91–150 million tons annually

Storing the Excess CO₂ supply

<table>
<thead>
<tr>
<th>RRC District</th>
<th>Depleted fields in billion tons</th>
<th>CO₂ storage billion tons/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>District 1</td>
<td>5.8</td>
<td>0.29</td>
</tr>
<tr>
<td>District 2</td>
<td>44.8</td>
<td>2.24</td>
</tr>
<tr>
<td>District 3</td>
<td>125.0</td>
<td>6.25</td>
</tr>
<tr>
<td>District 4</td>
<td>190.0</td>
<td>9.25</td>
</tr>
<tr>
<td>District 5</td>
<td>6.0</td>
<td>0.30</td>
</tr>
<tr>
<td>District 6</td>
<td>8.0</td>
<td>0.40</td>
</tr>
<tr>
<td>Total</td>
<td>380.0</td>
<td>19.00</td>
</tr>
</tbody>
</table>
3rd Step – Downsized to Match CO2 Demand

• Selected 11 power plants to match CO₂ demand of 31 major oil fields.
  ❖ 5 coal power plants total emission = 29.4 million tons
  ❖ 6 gas fired plants total emission = 12.3 – 25.5 million tons
  ❖ Total potential CO₂ supply = **41.7 – 55 million tons**

• CO₂ Demand for EOR and sequestration
  ❖ Total **806-831 million tons**
  ❖ Annual: **40-42 million tons/yr for 20 years**

Capture Technology

• Post combustion capture
  ❖ capture of CO₂ from flue gas produced by combustion.

• Relatively low CO₂ concentration in power plants make chemical absorption systems the dominant technology of interest for capture.

• Absorption process based on chemical solvents is currently the most commercially viable option for post-combustion technologies.
  ❖ Offers high capture efficiency
  ❖ Lowest energy use
### Capture Cost Assumptions

<table>
<thead>
<tr>
<th></th>
<th>Coal Retrofit</th>
<th>Gas Retrofit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min</td>
<td>Max</td>
</tr>
<tr>
<td>Capital cost: CC ($/kW) IPCC study (2005)</td>
<td>647</td>
<td>1,600</td>
</tr>
<tr>
<td>Other investments (land, etc.) % of capital cost</td>
<td>50%</td>
<td>50%</td>
</tr>
<tr>
<td>Economic life time (yr)</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>ROI (%)</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>Fuel costs $/mmBTU</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Fixed O&amp;M cost (% of CC)</td>
<td>10%</td>
<td>10%</td>
</tr>
<tr>
<td>Interest during construction</td>
<td>15%</td>
<td>15%</td>
</tr>
</tbody>
</table>

### CO2 Capture Chemicals: Cost Assumptions

<table>
<thead>
<tr>
<th></th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>MEA – Amine $/ton IPCC study (2005)</td>
<td>1,250</td>
<td>1,800</td>
</tr>
<tr>
<td>Alkaline (NaOH) $/ton</td>
<td>200</td>
<td>500</td>
</tr>
<tr>
<td>Activated Carbon $/ton</td>
<td>500</td>
<td>5,000</td>
</tr>
</tbody>
</table>
### Existing Coal Power plants in Gulf Coast Region, Texas

<table>
<thead>
<tr>
<th>Annual incremental expenses Power plant section</th>
<th>CO2 capture equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ave. Availability</td>
<td>0.85</td>
</tr>
<tr>
<td>Total capacity</td>
<td>6,571</td>
</tr>
<tr>
<td>Ave. electric efficiency.</td>
<td>35%</td>
</tr>
<tr>
<td>Total CO2 emissions</td>
<td>~77 million tons/yr</td>
</tr>
<tr>
<td>Incremental fixed O &amp; M cost</td>
<td>$43-45 million</td>
</tr>
<tr>
<td>Incremental variable O&amp;M cost</td>
<td>$4.4-9.8 million</td>
</tr>
<tr>
<td>Incremental fuel cost</td>
<td>$213-236 million</td>
</tr>
</tbody>
</table>

**Total CO2 emissions:** ~77 million tons/yr

**Total capacity:** 6,571

**Ave. electric efficiency:** 35%

**Incremental fixed O & M cost:** $43-45 million

**Incremental variable O&M cost:** $4.4-9.8 million

**Incremental fuel cost:** $213-236 million

**Assumed CO2 capture fraction:** 90%

**Total capital cost:** $1.1-3.1 billion

**Tot. fixed O&M cost:** $111-306 million

**Tot. variable O&M:** $21-248 million

**Total cost of capture:** $17-37/ton

### Existing Gas Power Plants in Gulf Coast Region, Texas

<table>
<thead>
<tr>
<th>Annual incremental expenses Power plant section</th>
<th>CO2 capture equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg. availability</td>
<td>0.37</td>
</tr>
<tr>
<td>Total capacity</td>
<td>20,193</td>
</tr>
<tr>
<td>Ave. electric efficiency.</td>
<td>35%</td>
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<tr>
<td>Total CO2 emissions</td>
<td>~55 million tons/yr</td>
</tr>
<tr>
<td>Incremental fixed O &amp; M cost</td>
<td>$65-75 million</td>
</tr>
<tr>
<td>Incremental variable O&amp;M cost</td>
<td>$16-43 million</td>
</tr>
<tr>
<td>Incremental fuel cost</td>
<td>$676-796 million</td>
</tr>
</tbody>
</table>

**Total CO2 emissions:** ~55 million tons/yr

**Total capacity:** 20,193

**Ave. electric efficiency:** 35%

**Incremental fixed O & M cost:** $65-75 million

**Incremental variable O&M cost:** $16-43 million

**Incremental fuel cost:** $676-796 million

**Assumed CO2 capture fraction:** 85%

**Total capital cost:** $1.78-3.25 billion

**Tot. fixed O&M cost:** $178-325 million

**Tot. variable O&M:** $13-154 million

**Total cost of capture:**
- $31-51/ton (CF≤40%)
- $21-32/ton (CF≥70%)
Cost comparisons

• Cost tilts to the low-side depending on
  – Land availability for retrofit
  – Rehabilitation of existing plant to cope with retrofit.
  – Capture efficiency envisioned; higher capture higher cost
  – Cost of CO2 solvent
  – Cost of other chemicals
    • NaOH, activated charcoal, etc.
• Cost of capture is generally lower for coal plants than for gas plants.
• Cost of capture of retrofits are about 1½ times lower than cost of capture of complete new power plants with capture.
  – The assumption is that the cost of the existing power plants is largely a sunk cost, if not already fully or partly recovered.

Selecting CO₂ Pipeline Parameters

• Pipe parameters
  – Size (diameter); Wall thickness; Length, Grade (class); Material; Roughness; Drag factor
• Fluid parameters
  – Density of gas, Molecular weight, Viscosity, Compressibility
• Heat transfer parameters
  – Inlet temp.; Soil temp.; Burial depth; Soil conductivity; Heat transfer coefficient
• Compressor parameters
  – Unit/type; fuel type; Compression ratio; Efficiency; Ambient temp.; Heat rate; Heat constant; Flow rate; Gas composition; Gas temperature
• System parameters
  – Supply and demand forecast; Sources and Delivery locations; Maximum and Minimum operating pressures; Operating temperature; (temperature profiles); Elevation changes.
Pipeline estimates

- Average expected initial compression pressure (from the capture point): **1533 psi (13 MPa)**
- Expected average final pressure arriving at the delivery point: **1189 psi (8.13 MPa)**
- Threshold (critical pressure) 1071 psi (7.38 MPa)
- Estimated final total pipeline network cost
  - $515 – 783 million (984-1,291 miles, 18-20 inches)
  - $531,300 – 607,000 per mile

Summary: Status of Input Data

**BEG**

- Cost of Capture $/tCO₂
  - Existing coal fired: 17-37 (fuel price of $1.89/GJ)
  - Existing gas fired: 48-72 (cf<40%) 38-52 (cf>70%) (Gas price $6.63/GJ)

- CO₂ pipeline network
  - Cost per km
    - $323,000 – 377,000 per km
  - Transportation $/tonne CO₂ per 250 km
    - $2

**International**

- Cost of capture $/tCO₂
  - Existing Coal fired 31-56 (fuel price of $1 - 3.2/GJ)
  - Gas fired 33-57 (Gas price of $3.13 - 5.0/GJ)

- CO₂ pipeline network
  - Cost per km
    - $330,000 (Great Plains, N. Dakota to Weyburn EOR project, 1997)

- Transportation $/tonne CO₂ per 250 km
  - $1-8 (IPCC findings, 2005)