Assessment of Strategies Proposed to Reduce CO₂ Emissions

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CO₂ Summit
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CCS Depends on a Suite of Technologies

• Separation
  – Absorption, adsorption, membranes

• Transportation
  – Transportation via pipelines (the most viable option)

• Storage
  – Storage in aquifers, deep ocean, oil fields, coal seams

CO₂ is captured (a), transported (b) and stored (c)

Statoil Sleipner facility: stores CO₂ in an aquifer below the North Sea

CO₂ Ocean Injection at Monterey Bay, CA

Monterey Bay, California (2006)

RV Western Flyer, MBARI


The Hydrate Reactor was Developed at ORNL


CO₂ Hydrate Reactor

CO₂ + nH₂O ⇌ CO₂·nH₂O

Tsouris et al., AICHE J., (2007)
There are Various Options for CO₂ Geologic Storage

1. Depleted Oil and Gas Reservoirs
2. CO₂ EOR and CO₂ EGR
3. Deep Saline Aquifers
4. CO₂ Enhanced Coal Bed Methane

CO₂ Transportation is a Mature Technology

~3,500 Miles of CO₂ pipelines transport ~30MtCO₂ per year for EOR activities

Construction of Green Pipeline, Denbury Resources

CO₂ Capture is the Biggest Challenge to CCS

CO₂ Capture & Compression • $1.5 billion capital

The Cost of CO₂ Capture Varies with Capture Efficiency

Expect a significant cost for CO₂ capture and compression

Ciferno, 2008
Virtual CCS: A New Concept
- Calculated the resources needed for CCS to stabilize CO₂ emissions
- Used this “pool” of money to build, maintain, operate, and decommission alternative energy installations (Virtual CCS)
- Based calculations on the Pacala and Socolow (2004) eight-wedge stabilization triangle

800 GtCO₂ must be avoided over 50 years!

Additional Data Used in the Model
- Capacity factor affects role of renewable energy:
  - Capacity factor:
    - 90% for nuclear - baseload
    - 90% for geothermal - baseload
    - 30% for wind - peak
  - Nuclear and geothermal are easily integrated to the current grid system
- Following the scenario of Pacala and Socolow:
  - Assume CCS lasts from 2010 to 2060 (50 years)
  - Goal is to stabilize CO₂ emissions at 2010 level, thus avoiding all increased emissions

Model Input Data for Comparison of CCS with Wind, Nuclear, and Geothermal Power
- Data taken from the literature determine the scale of CCS and alternative solutions:

<table>
<thead>
<tr>
<th>CO₂ emissions in 2010 (GT)</th>
<th>CO₂ emissions increase (GT/year)</th>
<th>Cost of CCS ($/ton CO₂)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>0.64</td>
<td>51</td>
</tr>
</tbody>
</table>

- These data lead to a total, one-wedge cost of $5.1 trillion over a period of 50 years
- Cost and revenue data for wind and nuclear energy:

<table>
<thead>
<tr>
<th>Geothermal installed cost ($/kW)</th>
<th>Geothermal revenue ($/kW-yr)</th>
<th>Nuclear installed cost ($/kW)</th>
<th>Nuclear revenue ($/kW-yr)</th>
<th>Wind installed cost ($/kW)</th>
<th>Wind revenue ($/kW-yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2778</td>
<td>438</td>
<td>5046</td>
<td>433</td>
<td>5700</td>
<td>390</td>
</tr>
</tbody>
</table>

’une IPCC Report ²Waste disposal cost included

Wind and Nuclear Power Avoid More Carbon Dioxide Emissions than CCS
- For a 25-year lifetime, windmills avoid 1.9 times more CO₂ than CCS per dollar in overall investment (capital plus operation).
- For a 50-year lifetime, nuclear power plants can avoid 4.3 times more CO₂ than CCS per dollar in overall investment (capital plus operation).
### Alternative Energy Generates Revenue

![Graph showing CCS cost, windmill revenue, and nuclear revenue over time.](image)

Tsouris et al., ES&T, 2010

### Comparison of CCS and Alternative Energy Shows Alternatives are Better Options

**CO₂ avoidance and revenue for a $5.1 trillion investment (1 wedge*)**

<table>
<thead>
<tr>
<th>Technology</th>
<th>Carbon avoidance ratio</th>
<th>Revenue ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCS</td>
<td>1</td>
<td>–</td>
</tr>
<tr>
<td>Wind</td>
<td>1.91</td>
<td>9.1 T</td>
</tr>
<tr>
<td>Nuclear</td>
<td>4.31</td>
<td>22 T</td>
</tr>
<tr>
<td>Geothermal</td>
<td>4.50</td>
<td>27 T</td>
</tr>
</tbody>
</table>

*1 wedge = 100 GtCO₂ avoided over 50 years

### Virtual CCS Can Help Reduce CO₂ Emissions More Effectively than CCS

![Diagram illustrating virtual CCS](image)

Tsouris et al., ES&T, 2010

### We Can More Effectively Stabilize the CO₂ Concentration in the Atmosphere by:

- Continuing CCS applications that generate revenue (i.e., EOR)
- Ranking carbon avoidance strategies based on effectiveness ratio over CCS and economic performance
- Pursuing virtual CCS, starting from the most promising energy strategies based on ranking
  - Investing resources planned for CCS into low-CO₂ energy technologies
  - Investing in both baseload and peak energy technologies

Virtual CCS is a more sustainable approach because it reduces carbon emissions more effectively and economically than CCS.