Status Report
Cryogenic Carbon Capture™

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Agenda

- Review CCC process
- Outline Economics
- Development stage
  - Current bench results
  - Skid development
  - Pilot plans
  - Demonstration
- Future Plans
CCS Impact on Efficiency

<table>
<thead>
<tr>
<th>Case</th>
<th>Type</th>
<th>Net Efficiency, HHV (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>SC/Air</td>
<td>39.4</td>
</tr>
<tr>
<td>2</td>
<td>USC/Air</td>
<td>44.6</td>
</tr>
<tr>
<td>3</td>
<td>SC/Air</td>
<td>28.3</td>
</tr>
<tr>
<td>4</td>
<td>USC/Air</td>
<td>33.2</td>
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<tr>
<td>5</td>
<td>SC/ASU</td>
<td>29.3</td>
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<tr>
<td>6</td>
<td>USC/ASU</td>
<td>33.0</td>
</tr>
<tr>
<td>7</td>
<td>SC/ITM</td>
<td>29.1</td>
</tr>
</tbody>
</table>
CCS Costs

Without CO₂ Capture

With CO₂ Capture

Levelized COE (cents/kWh)

Case 1
SC/Air
6.32

Case 2
USC/Air
6.43

Case 3
USC/Air
11.30

Case 4
USC/Air
10.66

Case 5
SC/ASU
10.47

Case 6
USC/ASU
9.98

Case 7
SC/ITM
10.58

Legend:
- TS&M
- Fuel
- Variable O&M
- Fixed O&M
- Capital
Value of Bolt-on Technology

![Graph showing relative LCOE for different scenarios: No CCS, CCC cost, Retrofit + CCC, Replace + CCC. The graph compares 29% Power Loss and 12% Power Loss.](image-url)
Cryogenic CO₂ Capture

Flowchart:
- Flue Gas to Condensing Heat Exchanger
- Condensed Gas to Dry Gas Heat Exchanger
- Dry Gas to Compressor
- Compressed Gas to Heat Exchanger
- Heat Exchanger to Liquid Pump
- Liquid Pump to Separator
- Separator to Expansion
- Expansion to Solid-gas Separator
- Solid-gas Separator to Solid CO₂ Bypass
- Solid CO₂ Bypass to Solids Compressor
- Solids Compressor to Solid CO₂ Stream
- Solid CO₂ Stream to Gaseous N₂-rich Stream
- Gaseous N₂-rich Stream to Pressurized Liquid CO₂ Stream
- Pressurized Liquid CO₂ Stream to SO₂, NO₂, Hg, HCl, etc.
- SO₂, NO₂, Hg, HCl, etc. to Liquid Pump
ASU Comparison

**ASU**
- Heat Exchange: Small
- HP Distillation: Large
- Utilization: Intermediate
- Compression: None

**CCC**
- Utilization: Smaller
- Heat Exchange: None
- HP Distillation: Very Small
- Compression: None
Data from DOE reports 2007/1281, 2007/1291, and Baxter et al, 2010
Fractional CCS Cost Increase

Data from DOE reports 2007/1281, 2007/1291, and Baxter et al, 2010
Cost Breakdown

Cost dominated by equipment and fuel – both issues that can be technically addressed.

Energy Efficiency

CO₂ capture efficiency

- 72% Efficient Compressor
- 87% Efficient Compressor

Specific Energy (GJ/ton CO₂ captured)
Desublimating Heat Exchangers

- Standard heat exchangers cannot handle solids formation on surfaces
- SES has designed and built 3 desublimating heat exchangers (patents filed on all)
Live-action Carbon Capture
Initial HX #2 Data

- Brief 9 minute run sampling gases at various locations within the heat exchanger
- Data agrees well with BYU model
HX #1 – CO₂ Capture

- Tested using a mixture of 14% CO₂ and 86% N₂
- Realized 92% CO₂ capture over a 2 hour run with no degradation in the process (ΔT and ΔP)
This heat exchanger was tested to verify that SO₂ could be captured.

Initial concentration 14% CO₂, 400 ppm SO₂ with the balance N₂.

Mean SO₂ capture is 99.8% which is the detection limit of the instrument.
Mercury Removal

- The CCC process also removes mercury, NO$_2$, HCl and many other species.
- Models show that mercury can be reduced to $10^{-8}$ ppm, but this result is not easily measured and thus has not been tested.
## Ancillary Pollutant Capture

<table>
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<tr>
<th>Temperature</th>
<th>-117.7 °C</th>
<th>-133.25 °C</th>
<th>-145.98 °C</th>
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<tbody>
<tr>
<td>Units</td>
<td>ppm</td>
<td>ppm</td>
<td>ppm</td>
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<tr>
<td>CO₂ Capture†</td>
<td>90%</td>
<td>99%</td>
<td>99.9%</td>
</tr>
<tr>
<td>Species</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO₂</td>
<td>17 341</td>
<td>1762</td>
<td>176.4</td>
</tr>
<tr>
<td>SO₂</td>
<td>5-0.1</td>
<td>&lt; 0.8*</td>
<td>≪ 0.8*</td>
</tr>
<tr>
<td>SO₃</td>
<td>0.0022*</td>
<td>2.75e-5*</td>
<td>3.3e-7*</td>
</tr>
<tr>
<td>NO₂</td>
<td>&lt; 1*</td>
<td>≪ 1*</td>
<td>≪ 1*</td>
</tr>
<tr>
<td>NO</td>
<td>initial amount</td>
<td>initial amount</td>
<td>initial amount</td>
</tr>
<tr>
<td>Hg</td>
<td>4e-10* (&lt;6e-7)</td>
<td>≈ 0</td>
<td>≈ 0</td>
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<tr>
<td>Other Air Toxics</td>
<td>&lt; Hg</td>
<td>&lt; Hg</td>
<td>&lt; Hg</td>
</tr>
</tbody>
</table>

†Assuming 15% initial dry CO₂ volume/mole fraction
*No data available – extrapolated correlation
CO2 particle size distribution

Cumulative size distribution

Vol % in size bin vs Particle Size (microns)

Data

BYU
Materials Tests
\(\Delta T_1\) suffices to drive a process that produces a product near its initial temperature, far less cooling than a traditional refrigeration cycle requires.

\(\Delta T_2\) corresponds to traditional refrigeration.
Basic Principles

\[ \Delta T_1 \] is twice as large for an external loop with the same temperature driving force as for direct compression.

Twice the flow rate (flue gas and refrigerant) requires double equipment size and heat leaks.
Capture Efficiency at 1 atm

Flue Gas Composition
- 14% CO₂ dry basis
- 10% CO₂ dry basis
- 5% CO₂ dry basis
- 1% CO₂ dry basis

Capture Efficiency (%) vs. Temperature (°C)
CO2 Collected at SES
Capture Efficiency

Minimum Flue Gas Temperature, °C

Capture Efficiency

- Observed Capture
- Aspen Model
## Figures of Merit

<table>
<thead>
<tr>
<th>Variable</th>
<th>Units</th>
<th>Simple System</th>
<th>Complex System</th>
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<tbody>
<tr>
<td>CO₂ In</td>
<td>kg/hr</td>
<td>706073</td>
<td>730057 (13.5%)</td>
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<tr>
<td>CO₂ Captured</td>
<td>kg/hr</td>
<td>702122</td>
<td>657108</td>
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<tr>
<td>Compression Energy</td>
<td>kW</td>
<td>175626</td>
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<tr>
<td>Expander Energy</td>
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<td>Pump Energy</td>
<td>kW</td>
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<td>Supplemental Refrig Energy</td>
<td>kW</td>
<td>17600</td>
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<tr>
<td>Specific Energy</td>
<td>GJ/tonne</td>
<td>0.601</td>
<td>0.620</td>
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<tr>
<td>CO₂ Capture Efficiency</td>
<td>-</td>
<td>0.995</td>
<td>0.90</td>
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<td>SOₓ Capture Efficiency</td>
<td>-</td>
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<td>NOₓ Capture Efficiency</td>
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<tr>
<td>Cl₂/HCl Capture Efficiency</td>
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<td>Hg Capture Efficiency</td>
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<tr>
<td>Usable H₂O Recovery</td>
<td>-</td>
<td>0.91</td>
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<tr>
<td>CO₂ Purity in Captured Stream</td>
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Current Status

- Analyses and modeling complete
- Laboratory-scale components complete
- Bench-scale components complete
- Skid-scale CFG process under construction
- Skid-scale ECL process under construction
- Pilot-scale system design initiated