CO₂ Capture Technologies – An Overview

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Whole Value Chain Carbon Capture, Utilization, and Storage (CCUS)

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Presentation Outline

I. Sources of CO₂ and Decarbonization Routes
   A. Global emissions and Decarbonizing the energy infrastructure
   B. Sources of CO₂ and Thermodynamics
   C. Appreciating the scale

II. Types of CO₂ Capture Technologies
   A. Pre- and Post-combustion capture
   B. Negative carbon emissions (DAC and BECCS)
   C. Challenges and Drivers

III. Status of CC & Next Generation Capture Technologies
   A. TRLs, Projects and Demonstrations
   B. Other Tech – Carbonate fuel cell systems

IV. Summary Thoughts – A Systems Perspective
Future of World Net Electricity Generation by Source

- Fossil use remains high with renewables growing
- In conflict with today’s tech trends
  - Phase out of IC engines seemingly imminent (France, U.K., Sweden,…)
  - Coal power generation down, huge adoption of RE technology in U.S.
  - Large gas turbine sales down (Siemens and GE)

EIA, *International Energy Outlook, 2016*
R. Gupta, *Sustainable power production, ASME ES 2016*
A snapshot of global CO₂ emissions - 2014

- 2018 on pace to set record emissions

~34 Gt CO₂

- 23% Industry

- 21% Transportation

- 38% Power generation

A. Global fossil fuel & industry emissions, 2014 (33.9 Gt CO₂)

B. Difficult-to-eliminate emissions, 2014 (9.2 Gt CO₂)

Davis et al., *Science* 360, (2018)
How to Reduce CO₂ Emissions To Meet <2°C Threshold?

- Let’s take a systems-level view first
Decarbonization of energy supply chains for closed-carbon cycle (neutrality) and increased renewables.
The majority of CO$_2$ sources are moderate to extremely dilute

<table>
<thead>
<tr>
<th>Category</th>
<th>% CO$_2$ (vol)</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Pressure</td>
<td>varies</td>
<td>Gas Wells (e.g., Sleipner) Synthesis Gas (e.g., IGCC)</td>
</tr>
<tr>
<td>High Purity</td>
<td>90-100%</td>
<td>Ethanol Plants Ammonia</td>
</tr>
<tr>
<td>Dilute to Moderate</td>
<td>10-15%</td>
<td>Coal-Fired Power Plants $\rightarrow$ ~ 40% of emissions</td>
</tr>
<tr>
<td>Very Dilute</td>
<td>3-7%</td>
<td>Natural Gas Boilers Gas Turbines $\rightarrow$ ~ 20% of emissions</td>
</tr>
<tr>
<td>Extremely Dilute</td>
<td>0.04 – 1%</td>
<td>Ambient Air $\rightarrow$ ~ 25% of emissions (transport sector)</td>
</tr>
</tbody>
</table>
Thermodynamics sets the *minimum* work requirements for separation processes

\[
W_{\text{min}} = RT \left[ n_B^{\text{CO}_2} \ln(y_B^{\text{CO}_2}) + n_B^{\text{B-CO}_2} \ln(y_B^{\text{B-CO}_2}) \right] + RT \left[ n_C^{\text{CO}_2} \ln(y_C^{\text{CO}_2}) + n_C^{\text{C-CO}_2} \ln(y_C^{\text{C-CO}_2}) \right] \\
-RT \left[ n_A^{\text{CO}_2} \ln(y_A^{\text{CO}_2}) + n_A^{\text{A-CO}_2} \ln(y_A^{\text{A-CO}_2}) \right]
\]

*for constant pressure*

The minimum work of separation decreases with increasing CO₂ concentration

- Energy scales with dilution
  - Can amount to 10% of power produced
- DAC is about \( \sim 20 \text{ kJ/mol } \text{CO}_2 \), regardless of % capture and purity
- Natural gas and coal range from 5-9 kJ/mol

**Other notes:**
- Density changes with purity
  - \( 95\% \text{ CO}_2 + 5\% \text{ N}_2 = 681 \text{ kg/m}^3 \)
  - \( 80\% \text{ CO}_2 + 20\% \text{ N}_2 = 343 \text{ kg/m}^3 \)
  - \( \sim 0.5 \text{ kJ/mol } \text{CO}_2 \) additional compression energy!

Appreciating the per capita scale of carbon capture

- US population ≈ 320,000,000
- CH population ≈ 1,370,000,000
- Annual emissions per capita:
  - US ≈ 16 tons CO₂
  - CH ≈ 7 tons CO₂
- Depending on sorbent loading and performance (cycling)
  - 16 tons → total 150 tons material

Just the CO₂ per person in US!

Just the sorbent + CO₂ per person in US!
The world will need 100 carbon capture and storage (CCS) plants by 2020 and \textbf{3400} by 2050 in order to reduce greenhouse gas emissions by \textbf{50\%}.

That equates to building a CCS plant every three days from 2020.

\textit{-International Energy Agency}
Conventional Coal-Fired Power Plant

- Technology is down-trending significantly, but total elimination in next 20-yrs is doubtful.

\[ \eta_{th} = 33 - 40\% \text{ (LHV)} \]
Carbon Capture (CC) Strategies: Post-Combustion (Retrofit-end of pipe)

Coal + Air → CO₂ + H₂O + N₂ + Contam. + Heat (Fuel)

Key Challenges:
- Low CO₂ concentration (10-15%)
- Contaminants
- High flue gas flow (2-3 million cfm @ 550 MW)
- Integration with steam cycle

Relevant Technologies (TRL 6+):
- Chemical absorption (MDEA), Calcium looping, Solid sorbents, Polymeric membranes, Molten carbonate fuel cells
Carbon Capture (CC) Strategies: Oxy-Combustion (Front-end Retrofit)

Coal + O_2 \rightarrow CO_2 + H_2O + Contam. + Heat (Fuel)

**Method:**
- Use air separation plant to produce O_2 for combustion
- After cleanup, flue gas contains high CO_2 concentration at low P

**Key Challenges:**
- Cost of air separation
- Temperature control in boiler
- Boiler design/retrofit

**Relevant Technologies (TRL 6+):**
- Solid adsorbents, High temperature chemical looping, Ionic transport membranes

Easier separation with: 50-95% CO_2 (depending on partial firing, etc.)
Carbon Capture (CC) Strategies: Pre-Combustion (System-wide change)

Coal + O₂ + H₂O → CO/CO₂ + H₂/H₂O + Contam. (Fuel)

**Method:**
- Gasifier to make syngas
- Water-gas shift to convert CO to H₂/CO₂
- Separate the CO₂ and H₂

**Key Challenges:**
- Process complexity and cost
- Additional process requirements
  - (ASU, WGS, thermal integration, H₂ turbine)
- Systems Integration

**Efficiency penalties**
- NGCC 7-11% (Selexol, Rectisol, membranes) for 85-94% CC

**Relevant Technologies (TRL 6+):**
- Physical solvents (Rectisol, Selexol, Purisol), Solid sorbents

Adapted from: R. Gupta, Sustainable power production, ASME ES 2016
There are many CC technologies under development and many commercial already

- The capture route depends, in part, on the CO₂ source
- Absorption, Adsorption, and Membrane Separations are the primary technology classifications

Post-Combustion CC technology features both highest TRL and most R&D activity

- Most mature P-C technology is absorption via monoethanolamines
- Commercially available tech dominated by solvent-based processes

Drivers:
- High thermal req’mts (steam for regen of solvent)
- Parasitic electrical energy (compression of CO2)
- High capital costs
  - Extremely large process equipment
  - Expensive materials due to corrosion resistance
  - Evaporative losses and wastewater treatment
  - Large plant footprint

Result:
- Increase in COE > 65%
- Reduction in Efficiency ~10%
- Cost of Avoided CO₂ > $60/ton
Amine scrubbing absorption is state-of-the-art for point-source CO₂ capture

- In absorber: CO₂ dissolves into liquid solvent, reacts w/ binding agent in liquid
- In stripper: process is reversed
- **Solvent regeneration dominates energy requirements**

Advances in solvent-absorption lie in solvent improvement

**Desirable solvent properties:**
- High CO₂ capacity
- Fast kinetics
- Low volatility & viscosity
- Relatively high density
- Nontoxic, nonflammable, and noncorrosive
- High thermal stability
- Resistance to oxidation

**Advanced R&D Focus:**
- Blended Amines
- Liquid-Solid Sorbents
  - Carbonates
  - Ammonia
- Reduce Regen Duty by 30-50%

Petra Nova – 1.4 Mt CO₂/year
115 Meters Tall Absorber

Gas to Liquid Flux

\[ J_{L,CO_2} = c_i k_L E \]

“CO₂-free” gas out

CO₂-loaded solvent out

Adapted from: Wilcox, Carbon Capture, Springer, 2012
Carbon negative emissions via DAC and BECCS may be attractive for capturing difficult / past emissions.

Figures adapted from: NAS, Climate Intervention, (2015)
DOE targets for advancement in CC for power generation

- However, note many projects being executed for industrial applications

Advanced CC Technologies – Hybrid Solution
Electrochemical Membrane & Power Gen

Molten Carbonate Fuel Cells

The driving force for CO₂ separation is electrochemical potential, not pressure differential across the membrane.

Net Results

- Simultaneous Power Production and CO₂ Separation from Flue Gas of an Existing Facility
- Excess Process Water Byproduct
- Complete Selectivity towards CO₂ as Compared to N₂

Re-application of commercial fuel cell technology for CC and additional power gen

Fuel Cell Energy in partnership with AECOM and Southern Company ($30M DOE NETL)

<table>
<thead>
<tr>
<th>Operating Mode</th>
<th>90% Capture Coal-Derived FG</th>
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<tr>
<td>MCFC Gross Power, DC</td>
<td>1863.4 kW</td>
</tr>
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**Energy & Water Input**

- Natural Gas Fuel Flow: 169.4 scfm
- Fuel Energy (LHV): 2877.8 kW
- Water Consumed/(Produced): (1.8) gpm

**Consumed Power**

- AC Power Consumption: (611.0) kW
- Inverter Loss: 74.5 kW
- Total Parasitic Power Consumption: (685.6) kW

**Net Generation & Efficiency**

- CEPACS Plant Net AC Output: 1177.8 kW
- Electrical Efficiency (LHV): 40.9%

**Carbon Capture**

- Total Carbon Capture, %: 92%
- Carbon Capture from FG, %: 90%
- Total CO2 Captured, Tons per Day: 67 T/D
- CO2 Purity: 99.6%
WHAT CC TECHNOLOGIES ARE READY TO PROVIDE A SOLUTION?
Technology Readiness Levels of various CO₂ capture technologies

<table>
<thead>
<tr>
<th>Concept</th>
<th>Formulation</th>
<th>Proof of concept (lab tests)</th>
<th>Lab prototype</th>
<th>Lab-scale plant</th>
<th>Pilot plant</th>
<th>Demonstration</th>
<th>Commercial Refinement required</th>
<th>Commercial</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRL1</td>
<td>TRL2</td>
<td>TRL3</td>
<td>TRL4</td>
<td>TRL5</td>
<td>TRL6</td>
<td>TRL7</td>
<td>TRL8</td>
<td>TRL9</td>
</tr>
</tbody>
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**Bui et al., Energy Environ. Sci., 2018, 11,1062**
Only 2 Power Plant CCS demonstration projects are operational

<table>
<thead>
<tr>
<th>Project</th>
<th>Boundary Dam</th>
<th>Kemper</th>
<th>Petra Nova</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Location</strong></td>
<td>Saskatchewan, Canada</td>
<td>Mississippi, USA</td>
<td>Texas, USA</td>
</tr>
<tr>
<td><strong>Start date</strong></td>
<td>Oct 2014</td>
<td>Jan 2017 (?)</td>
<td>Dec 29, 2016</td>
</tr>
<tr>
<td><strong>Size (MW)</strong></td>
<td>115 (net)</td>
<td>582 (net) 240 (gross)</td>
<td></td>
</tr>
<tr>
<td><strong>Size (Mt CO₂/yr)</strong></td>
<td>1.3</td>
<td>3.0</td>
<td>1.4</td>
</tr>
<tr>
<td><strong>New/Retrofit</strong></td>
<td>Retrofit</td>
<td>New IGCC (NGCC)</td>
<td>Retrofit</td>
</tr>
<tr>
<td><strong>Plant Type</strong></td>
<td>PC</td>
<td>PC</td>
<td>PC</td>
</tr>
<tr>
<td><strong>Steam Source</strong></td>
<td>Steam Turbines</td>
<td>——</td>
<td>NG Cogeneration Plant</td>
</tr>
<tr>
<td><strong>Solvent</strong></td>
<td>Shell Cansolv</td>
<td>Selexol/TRIG</td>
<td>MHI KS-1</td>
</tr>
<tr>
<td><strong>Initial Cost Estimate</strong></td>
<td>$1.1 billion</td>
<td>$2.4 billion</td>
<td>$1 billion</td>
</tr>
<tr>
<td><strong>Actual Cost (est)</strong></td>
<td>$1.5 billion</td>
<td>$7.5 billion</td>
<td>$1 billion</td>
</tr>
</tbody>
</table>
Boundary Dam
World’s first CCS Power Plant

110 MW Power Plant in Canada
near border of North Dakota
Petra Nova
-Houston, TX

240 MW Power Plant
Most large-scale CCS demonstrations are in the U.S. and are dominated by EOR applications.

Final thoughts from a Systems Integration Perspective

- Huge focus on power generation studies & tech development, yet vast majority of operational CCS projects are in industrial sector

- Realizing deep decarbonization goals requires solution sets that vary depending on resource mix (wind/solar [CSP, PV], geothermal, biomass, gas-CCS, nuclear)

- Few CC technologies address past emissions (DAC, BECCS)

- Firming capacity of technologies may be important for grid-integration → Dispatch/Storage considerations...
  - Post-combustion such as amine regeneration, could be scheduled at times of excess power enabling output to be boosted when required.
  - Pre-combustion or oxy-fuel capture, an oxygen buffer would allow the air separation unit to run independently of generation to maximize revenue/cost effectiveness (e.g., operate ASU during off-peak hours)

- Energy planning and Infrastructure transitions are needed
  - Energy conservation, carbon management, water, power
Integration of CO₂ capture, conversion, & storage with energy & water systems

Eventually, infrastructure redesign/expansion and energy planning will need to be dealt with.
Acknowledgements

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