CCS R&D at EPRI

Abhoyjit S. Bhowm
Electric Power Research Institute

NETL CO₂ Capture Technology Project Review Meeting
August 8, 2016
Pittsburgh, PA
Electric Power Research Institute

Mission
Advancing safe, reliable, affordable and environmentally responsible electricity for society through global collaboration, thought leadership and science and technology innovation

Independent
Objective, scientifically based results address reliability, efficiency, affordability, health, safety and the environment

Nonprofit
Chartered to serve the public benefit

Collaborative
Bring together scientists, engineers, academic researchers, industry experts
EPRI Members

- 450+ participants in more than 30 countries
- EPRI members generate approximately 90% of the electricity in the United States
- International funding is nearly 25% of EPRI’s research, development and demonstrations
- Total Revenue ~$390 M
NOAA State of Climate Report 2015
Bulletin of the American Meteorological Society, 98 (8), August 2016

- Records set:
  - Highest global mean GHGs: 399.4 ppm CO₂, 1834 ppb CH₄, 328.2 ppb N₂O
  - Highest global mean surface temperature. 2nd straight year.
  - Highest number of extreme warm temperature events. Almost every continent
  - Highest sea surface temperature
  - Highest sea level
  - Highest ocean heat
  - Lowest levels of Artic sea ice

- Drought
  - Affects nearly all 1/3 global land surface. All continents.
  - 14% land surface in severe or extreme drought.

- Cyclones
  - 101 tropical cyclones vs average of 82
  - Three Category 4 storms in same basin for the first time ever

- Living systems
  - Plants and animals on the move
  - Some areas up to 8°C higher than average

- Glaciers, permafrost, …
A Cubic Mile of Oil

1 Cubic Mile Oil

\[ \approx 1.1 \text{ trillion gal oil} \]

\[ \approx 26 \text{ Billion bbl oil} \]

\[ \approx 153 \times 10^{15} \text{ Btu (Quads)} \]

\[ \approx 6.4 \text{ Billion tons coal} \]

\[ \approx 15.3 \text{ Trillion kWh electricity (10,000 BTU/kWh)} \]

Figure courtesy R. Malhotra/SRI International
Global Energy Consumption, CMO Units

Total Energy Consumption Increased +16.5%
Fossil Fuel Share Unchanged ~80%

Data from R. Malhotra/SRI International
Growth in Fossil $\cong 4x$ Growth in Non-Fossil

<table>
<thead>
<tr>
<th>Δ 2006 to 2014</th>
<th>CMO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fossil</td>
<td></td>
</tr>
<tr>
<td>Oil</td>
<td>0.08</td>
</tr>
<tr>
<td>Coal</td>
<td>0.21</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>0.13</td>
</tr>
<tr>
<td><strong>Sub-total</strong></td>
<td><strong>0.42</strong></td>
</tr>
<tr>
<td>Non-Fossil</td>
<td></td>
</tr>
<tr>
<td>Nuclear</td>
<td>-0.02</td>
</tr>
<tr>
<td>Hydro</td>
<td>0.05</td>
</tr>
<tr>
<td>Biomass</td>
<td>0.02</td>
</tr>
<tr>
<td>Solar + Wind</td>
<td>0.06</td>
</tr>
<tr>
<td><strong>Sub-total</strong></td>
<td><strong>0.11</strong></td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>0.53</strong></td>
</tr>
</tbody>
</table>

Data from R. Malhotra/SRI International

$\rightarrow$ CO$_2$ Emissions Continue

Data from [http://www.esrl.noaa.gov/gmd/ccgg/trends/](http://www.esrl.noaa.gov/gmd/ccgg/trends/)

CCS is the ONLY Option For Fossil Fuels
Energy Options by 2050

- Historical +2.6%/yr growth in energy consumption → Need ~9 CMO by 2050

- Fossil fuel reserves are 100’s CMO; resources are 1000’s CMO

<table>
<thead>
<tr>
<th>Option</th>
<th>Size</th>
<th>Availability</th>
<th>Needed for 1 CMO</th>
<th>Build by 2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydro</td>
<td>18 GWe</td>
<td>50%</td>
<td>200 Dams</td>
<td>1 every 2 months</td>
</tr>
<tr>
<td>Nuclear</td>
<td>900 MWe</td>
<td>90%</td>
<td>2200 Plants</td>
<td>6 every month</td>
</tr>
<tr>
<td>Solar Parks</td>
<td>900 MWe</td>
<td>25%</td>
<td>7000 Parks</td>
<td>5 every week</td>
</tr>
<tr>
<td>Windmills</td>
<td>1.65 MWe</td>
<td>35%</td>
<td>3 Million</td>
<td>2000 every week</td>
</tr>
<tr>
<td>Solar Rooftop</td>
<td>2.1 kWe</td>
<td>20%</td>
<td>4.2 Billion</td>
<td>380,000 every day</td>
</tr>
</tbody>
</table>

Fossil Fuels Are Unlikely to be Displaced in the Next Few Decades
# CO₂ Utilization for Chemicals

<table>
<thead>
<tr>
<th>Chemical</th>
<th>US Production, Estimated 2015</th>
<th></th>
<th></th>
<th>Global Production, Estimated 2015</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mt</td>
<td>Gmol</td>
<td>GWe Coal at 90% Capture</td>
<td>GWe Gas at 90% Capture</td>
<td>Mt</td>
<td>Gmol</td>
</tr>
<tr>
<td>1 Sulfuric Acid</td>
<td>39.3</td>
<td>401.1</td>
<td>2.3</td>
<td>5.6</td>
<td>210.0</td>
<td>2.1</td>
</tr>
<tr>
<td>2 Nitrogen</td>
<td>31.2</td>
<td>1114.8</td>
<td>6.4</td>
<td>15.5</td>
<td>123.8</td>
<td>4.4</td>
</tr>
<tr>
<td>3 Ethylene</td>
<td>26.0</td>
<td>813.9</td>
<td>4.6</td>
<td>11.3</td>
<td>150.0</td>
<td>4.7</td>
</tr>
<tr>
<td>4 Oxygen</td>
<td>24.4</td>
<td>869.4</td>
<td>5.0</td>
<td>12.1</td>
<td>88.7</td>
<td>3.2</td>
</tr>
<tr>
<td>5 Lime</td>
<td>19.9</td>
<td>355.3</td>
<td>2.0</td>
<td>4.9</td>
<td>367.1</td>
<td>6.5</td>
</tr>
<tr>
<td>46 Propylene Oxide</td>
<td>2.1</td>
<td>35.5</td>
<td>0.2</td>
<td>0.5</td>
<td>5.5</td>
<td>0.1</td>
</tr>
<tr>
<td>47 Phenolic Resins</td>
<td>1.5</td>
<td>14.7</td>
<td>0.1</td>
<td>0.2</td>
<td>6.0</td>
<td>0.1</td>
</tr>
<tr>
<td>48 Calcium Carbonate</td>
<td>3.1</td>
<td>31.5</td>
<td>0.2</td>
<td>0.4</td>
<td>14.7</td>
<td>0.1</td>
</tr>
<tr>
<td>49 Butadiene (1.3)</td>
<td>2.7</td>
<td>50.5</td>
<td>0.3</td>
<td>0.7</td>
<td>12.9</td>
<td>0.2</td>
</tr>
<tr>
<td>50 Nylon Resins &amp; Fibers</td>
<td>0.8</td>
<td>3.4</td>
<td>0.0</td>
<td>0.0</td>
<td>2.8</td>
<td>0.0</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>453</td>
<td>9368</td>
<td>53</td>
<td>130</td>
<td>2620</td>
<td>57</td>
</tr>
<tr>
<td>2015 Net Generation, GWe-yr</td>
<td></td>
<td></td>
<td>155</td>
<td>152</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO₂e from Electricity</td>
<td>2,000</td>
<td>45,500</td>
<td></td>
<td></td>
<td>10,500</td>
<td>239,000</td>
</tr>
<tr>
<td>CO₂e from All Sources</td>
<td>6,890</td>
<td>156,600</td>
<td></td>
<td></td>
<td>37,000</td>
<td>841,000</td>
</tr>
</tbody>
</table>

\[
R + CO_2 \rightarrow RCO_2
\]

Limited supplies of R & limited sales of RCO₂

CO₂ Emissions >> CO₂ Utilization
Utilization Schemes Often Overlook Life Cycle Analysis

- Urea production
  - \(2\text{NH}_3 + \text{CO}_2 \rightleftharpoons \text{H}_2\text{N-COONH}_4\text{H} \rightleftharpoons (\text{NH}_2)_2\text{CO} + \text{H}_2\text{O}\)
- But ammonia is manufactured by \(3\text{H}_2 + \text{N}_2 \rightleftharpoons 2\text{NH}_3\)
- And \(\text{H}_2\) is mostly generated by steam methane reforming:
  - \(\text{CH}_4 + 2\text{H}_2\text{O} \rightleftharpoons 3\text{H}_2 + \text{CO} + \text{H}_2\text{O} \rightleftharpoons 4\text{H}_2 + \text{CO}_2\)
- Overall balance: \(\frac{3}{4}\text{CH}_4 + 2\text{N}_2 + \frac{1}{2}\text{H}_2\text{O} + \text{CO}_2 \rightleftharpoons (\text{NH}_2)_2\text{CO} + \frac{3}{4}\text{CO}_2\)
- Net: \(\frac{1}{4}\) mole \(\text{CO}_2\) per mole of urea
- 90% capture from 200 MW coal generation:
  - 1,200,000 t/y \(\text{CO}_2\) captured \(\rightarrow\) 6,600,000 t/y urea produced
  - Represents >100% of US urea consumption

Cash Positive \(\neq\) \(\text{CO}_2\) Negative
Structure-Property Model for Solvent Screening

1. **Input**
   - Solvent Structure

2. **Test & tune**
   - Structure-property model against known solvents

3. **Thermo. Props.**
   - \( \Delta_f G \)
   - \( \Delta_f H \)
   - \( C_p \)
   - \( \gamma_i \)
   - \( H_i \)

4. **VLE**

5. **Output**
   - Imposed Load on Power Plant

6. **Use optimal properties**
   - To suggest new solvent structures
Structure-Property Model for 30 wt% MEA

Model Results for Known Solvents are Close to Experimental Data
Partial Capture on NGCC using Membranes

Can flue gas bypass the capture system?

What is effect of pressure?

Capture System

Natural gas

HRSG

Air

Carbon dioxide

Feed stage

Enriching stage

Stripping stage
Partial Capture on NGCC using Membranes with Energy Minimization

Effect of pressure

Effect of flue gas bypass

Lower pressure results in less energy (at expense of capital). Partial capture of CO₂ may require processing most of the flue gas.
Brine Extraction Storage Test
DOE Project DE-FE0026140

- Lower Tuscaloosa formation in SE U.S.
- Use waste water injection as a surrogate for CO$_2$
- Extract brine to manage reservoir pressure and control plume
- Treat brine (high TDS) to make usable water
Potential Cost to CCS

- **Phase I: 2015-16**
  - Initial assessment indicated brine treatment will add between $3-$25/t CO$_2$ but some estimates as high as $71/ tCO$_2$.
  - Cost depends heavily on the amount of brine extracted, chemistry of the brine, and the particular treatment technology employed.

- **Phase II: 2016-18**
  - Project team will conduct field tests at Gulf Power’s Plant Smith.
  - This will include a site where water treatment vendors can test their technologies on the extracted brine.
Together...Shaping the Future of Electricity