Energy Process Analysis

- Plant-level modeling, performance assessment
- Cost estimation for plant-level systems
- General plant-level technology evaluation and support

Energy Systems Analysis

Resource Availability and Cost Modeling
- CO₂ storage (saline and EOR)
- Fossil fuel extraction
- Rare earth elements
- General subsurface technology evaluation and support

Process Systems Engineering Research

- Process synthesis, design, optimization, intensification
- Steady state and dynamic process model development
- Uncertainty quantification
- Advanced process control

Energy Markets Analysis

Energy Economy Modeling and Impact Assessment
- Enhanced fossil energy representation
- Multi-model scenario/policy analysis
- Grid, infrastructure, energy-water

- Economic impact assessment
- General regulatory, market and financial expertise

Life Cycle Analysis (LCA)

Advanced Technology Design & Cost Estimation

Travis Shultz

Luciane Cunha, Ph.D.
Overview

• BECCS Study (includes LCA)
  ◦ Design Basis Review
  ◦ Performance Results
  ◦ Economic Results

• Ongoing Updates

• Questions

BECCS Key Research Questions:

1. Can co-firing biomass with coal reduce greenhouse gas (GHG) emissions on a life cycle basis?

2. Will adding biomass to coal-fired power plants increase or decrease the cost of electricity?

3. What is the optimal combination of coal and biomass to achieve low-carbon electricity and low costs?
Overview

• BECCS Study (includes LCA)
  ◦ Design Basis Review
  ◦ Performance Results
  ◦ Economic Results

• Ongoing Updates

• Questions
Site Characteristics

- Site characteristics and ambient conditions are consistent with Revision 4 of the Bituminous Baseline Study

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Greenfield, Midwestern U.S.</td>
</tr>
<tr>
<td>Topography</td>
<td>Level</td>
</tr>
<tr>
<td>Size (pulverized coal), acres</td>
<td>300</td>
</tr>
<tr>
<td>Size (natural gas combined cycle), acres</td>
<td>100</td>
</tr>
<tr>
<td>Transportation</td>
<td>Rail or Highway</td>
</tr>
<tr>
<td>Ash Disposal</td>
<td>Off-Site</td>
</tr>
<tr>
<td>Water</td>
<td>50% Municipal and 50% Ground Water</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elevation, m (ft)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>Barometric Pressure, MPa (psia)</td>
<td>0.101 (14.696)</td>
</tr>
<tr>
<td>Average Ambient Dry Bulb Temperature, °C (°F)</td>
<td>15 (59)</td>
</tr>
<tr>
<td>Average Ambient Wet Bulb Temperature, °C (°F)</td>
<td>10.8 (51.5)</td>
</tr>
<tr>
<td>Design Ambient Relative Humidity, %</td>
<td>60</td>
</tr>
<tr>
<td>Cooling Water Temperature, °C (°F)</td>
<td>15.6 (60)</td>
</tr>
<tr>
<td>Air composition based on published psychrometric data, mass %</td>
<td>100.0</td>
</tr>
<tr>
<td>N₂</td>
<td>75.055</td>
</tr>
<tr>
<td>O₂</td>
<td>22.998</td>
</tr>
<tr>
<td>Ar</td>
<td>1.280</td>
</tr>
<tr>
<td>H₂O</td>
<td>0.616</td>
</tr>
<tr>
<td>CO₂</td>
<td>0.050</td>
</tr>
<tr>
<td>Total</td>
<td>100.00</td>
</tr>
</tbody>
</table>


\(^A\) The cooling water temperature is the cooling tower cooling water exit temperature; this is set to 8.5\(^\circ\) F above ambient wet bulb conditions in International Organization for Standardization (ISO) cases.
Fuel Characteristics

• The coal analysis is consistent with the Bituminous Baseline Rev4 analysis
• Biomass characteristics consistent with prior NETL report

<table>
<thead>
<tr>
<th>Ultimate Analysis (weight %)</th>
<th>As Received</th>
<th>Dry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture</td>
<td>50.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Carbon</td>
<td>26.18</td>
<td>52.36</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>2.80</td>
<td>5.60</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>0.19</td>
<td>0.37</td>
</tr>
<tr>
<td>Chlorine</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Sulfur</td>
<td>0.02</td>
<td>0.03</td>
</tr>
<tr>
<td>Ash</td>
<td>0.74</td>
<td>1.48</td>
</tr>
<tr>
<td>Oxygen&lt;sup&gt;a&lt;/sup&gt;</td>
<td>20.08</td>
<td>40.16</td>
</tr>
<tr>
<td>Total</td>
<td>100.0</td>
<td>100.0</td>
</tr>
<tr>
<td>HHV, kJ/kg (Btu/lb)</td>
<td>9,813 (4,219)</td>
<td>19,627 (8,438)</td>
</tr>
<tr>
<td>LHV, kJ/kg (Btu/lb)</td>
<td>9,232 (3,969)</td>
<td>18,464 (7,938)</td>
</tr>
<tr>
<td>HHV, kJ/kg (Btu/lb)</td>
<td>27,113 (11,666)</td>
<td>30,506 (13,126)</td>
</tr>
<tr>
<td>LHV, kJ/kg (Btu/lb)</td>
<td>26,151 (11,252)</td>
<td>29,544 (12,712)</td>
</tr>
</tbody>
</table>

<sup>a</sup>The proximate analysis assumes sulfur as volatile matter
<sup>b</sup>By difference

MATS and NSPS Limits

• The utility Mercury and Air Toxics Standards (MATS) and New Source Performance Standards (NSPS) limits for pulverized coal (PC) plants considered in the Bituminous Baseline Rev4 is adhered to

<table>
<thead>
<tr>
<th>MATS and NSPS Emission Limits for PM, HCl, SO₂, NOx, and Hg</th>
<th>PC (lb/MWh-gross)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SO₂</td>
<td>1.00</td>
</tr>
<tr>
<td>NOx</td>
<td>0.70</td>
</tr>
<tr>
<td>PM (Filterable)</td>
<td>0.09</td>
</tr>
<tr>
<td>Hg</td>
<td>3x10⁻⁶</td>
</tr>
<tr>
<td>HCl</td>
<td>0.010</td>
</tr>
</tbody>
</table>

*CO emissions were not considered, or reported, in BBR Rev 4*
Biomass Pre-Processing

• The current and prior studies assume that cut and sized hybrid poplar logs are received at the plant site by truck

• The logs are then pre-processed to improve the energy density, handling characteristics, and combustion efficiency of the hybrid poplar, as depicted below

Receiving/Unloading/Handling
  • Cut/sized logs
  • Field dried to 50 wt. % H₂O
  • 48,000 lb truck capacity

Chipping/Grinding
  • Size reduction (<5 mm) to facilitate drying and pelletizing steps

Drying
  • WTA drying process
  • Dry to 10 wt.% H₂O

Pelletizing
  • Improved physical properties for downstream storage and handling (e.g., pulverization, boiler injection)

Storage
  • 72 hours of short term storage
Design Assumptions

• Biomass is available in the quantity, type, frequency, and at the cost assumed in the study
• Biomass co-firing does not effect performance/cost of the carbon capture system
• Product CO₂ must meet requirements of NETL QGESS on CO₂ product purity¹
• Facility Capacity Factor = Availability = 85% for all cases
• Capital Cost Uncertainty Range -15%/+30% (AACE Class 4)²
• Use mature plant costing methodology²
  ◦ Initial plants will likely have higher costs when incorporating CCS and co-firing

Plant Configuration with CO₂ Capture

Note: Block Flow Diagram is not intended to represent a complete material balance. Only major process streams and equipment are shown.
Case Matrix

- The following case matrix was considered part of this study update:

  - 20 wt%
    - Lower end of co-firing
    - Represents the majority of currently in practice co-firing rates
    - Boiler efficiency impacts not statistically significant
  - 35 wt%
    - Mid-range of feasible co-firing
    - Close to the potential net-zero greenhouse gas emissions point (with capture)
    - If the desired result is for a net-zero LCA, this co-fire rate could be changed
  - 49 wt%
    - Current potential maximum rate of co-firing based on logistical supply constraints
    - Maintains coal with biomass co-firing idea
  - Case nomenclature: P – poplar, N – non-capture, A – amine, numericals – case designation

<table>
<thead>
<tr>
<th>Case</th>
<th>Biomass Type</th>
<th>Plant Type</th>
<th>% Biomass in Feed</th>
<th>CO₂ Capture %</th>
<th>Capture Strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td>PN1</td>
<td>Hybrid Poplar</td>
<td>Supercritical</td>
<td>20</td>
<td>0</td>
<td>N/A</td>
</tr>
<tr>
<td>PN2</td>
<td></td>
<td></td>
<td>35</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PN3</td>
<td></td>
<td></td>
<td>49</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PA1</td>
<td></td>
<td></td>
<td>20</td>
<td>90</td>
<td>Amine (Cansolv)</td>
</tr>
<tr>
<td>PA2</td>
<td></td>
<td></td>
<td>35</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PA3</td>
<td></td>
<td></td>
<td>49</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Overview

• BECCS Study (includes LCA)
  ◦ Design Basis Review
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  ◦ Economic Results

• Ongoing Updates

• Questions
Net Plant Efficiency

- Plant efficiency is reduced as co-firing percentages increase primarily due to two factors:
  - Hybrid poplar has a lower heating value compared to coal leading to a higher overall fuel consumption rate and lower efficiency
  - Increased auxiliary loads due to pelletization and drying biomass from 50 wt% down to 10 wt% moisture
Gross Plant CO₂ Emissions

• Carbon dioxide emissions within the plant boundary increase as co-fire rates increase again due in part to lower biomass fuel heating value and increased auxiliary load requirements.

• This does not include the carbon dioxide captured during the biomass growth cycle.
Overview

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• Ongoing Updates

• Questions
Total Overnight Cost/Total As Spent Cost (TOC/TASC)

• Total costs impacted as overall plant efficiency decreases with the co-fire rate increase

<table>
<thead>
<tr>
<th>wt% Biomass</th>
<th>% Increase TOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>5.3% 4.5%</td>
</tr>
<tr>
<td>35</td>
<td>8.4% 7.7%</td>
</tr>
<tr>
<td>49</td>
<td>12.1% 11.5%</td>
</tr>
</tbody>
</table>

[Bar chart showing TOC/TASC for different scenarios]
Levelized Cost of Electricity (LCOE)

- Levelized cost of electricity increases dominated by increased biomass fuel costs

<table>
<thead>
<tr>
<th>wt% Biomass</th>
<th>% Increase LCOE w/o Capture</th>
<th>% Increase LCOE w/ Capture</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>8.5%</td>
<td>9.0%</td>
</tr>
<tr>
<td>35</td>
<td>18.4%</td>
<td>17.5%</td>
</tr>
<tr>
<td>49</td>
<td>30.7%</td>
<td>28.3%</td>
</tr>
</tbody>
</table>
Breakeven CO$_2$ Sales Price/Penalty

- High biomass costs drive the breakeven sales price/penalty above that of Case B12B
- Including the Cansolv unit with cofiring reduces the marginal increases
- Cases presented do not consider lifecycle emissions
BECCS TEA Conclusions

• PC with CCS, 0% biomass, offers lowest breakeven CO$_2$ cost option

• High cost of carbon emissions or desire for carbon negative systems makes co-firing with biomass plus CCS attractive

• Carbon-neutral or –negative coal-fired electricity can be achieved by adding both biomass and CCS to PC systems
  ◦ Neutrality occurs near 35% Biomass with 90% CCS
Life Cycle GHG Emissions per MWh, busbar

Global Warming Potential [100-yr] (kg CO$_2$e/MWh)

- 0% Bio: 816 kg CO$_2$e/MWh
- 20% Bio: 773 kg CO$_2$e/MWh
- 35% Bio: 731 kg CO$_2$e/MWh
- 49% Bio: 680 kg CO$_2$e/MWh
- 0% Bio CCS: 149 kg CO$_2$e/MWh
- 20% Bio CCS: 72 kg CO$_2$e/MWh
- 35% Bio CCS: 7 kg CO$_2$e/MWh
- 49% Bio CCS: -104 kg CO$_2$e/MWh

Higher Biomass rates = larger land use requirements, can be reduced through application of higher capture rates (i.e. 95% capture with amines or CFB with oxy-combustion, etc.)

50% Lower than Wind or Solar LC GHG Emissions!
Overview

• BECCS Study (includes LCA)
  ◦ Design Basis Review
  ◦ Performance Results
  ◦ Economic Results

• Ongoing Updates

• Questions
• NETL has examined the use of EGR to increase the CO$_2$ concentration in NGCC flue gas to enable lower cost post-combustion capture of CO$_2$
  ◦ Current and Future Technologies for NGCC Power Plants, 2013
    DOE/NETL-341-061013
  ◦ Carbon Capture Approaches for NGCC Systems, Revision 2, 2010
    DOE/NETL-2011-1470

• Developing baseline cases for NGCC with EGR and CCS
  ◦ Focusing on parallel cases with B31B – F Class turbine
  ◦ Evaluating interim results w.r.t recent EPRI report$^1$

• Will develop an H-Class EGR with CCS case as well

$^1$Booras, G. “Natural Gas Combined Cycle Power Plants with Post-Combustion CCS”, EPRI Technical Update Report # 3002016289, August 2020
NGCC Retrofit Study

Updating NGCC Retrofit Report

• Will update NGCC retrofit report\(^1\) and Carbon Capture Retrofit Database (CCRD)\(^2\)
  ◦ Align with financial assumptions and performance updates of Rev 4 of Fossil Energy Baseline
  ◦ Calculate costs and performance based on retrofit design
    — Retrofit difficulty factors applied to capital cost
    — Derate energy cost accounted
  ◦ Will include F and H class cases
  ◦ Sensitivities
  ◦ Serves as basis for scaling factors used in CCRD for NGCC

• Also will be examining greater than 90% capture for NGCC (separate report)

• Update to PC retrofit report\(^3\) and CCRD\(^4\) to follow

2. NGCC CCRD, April 2019
   https://netl.doe.gov/energy-analysis/details?id=086796fb-e0d9-4d1d-831f-c2e986a7072e
3. Eliminating the Derate of Carbon Capture Retrofits, September 2011, DOE/NETL-401/091211
4. PC CCRD, April 2019
   https://netl.doe.gov/energy-analysis/details?id=69db8281-593f-4b2e-ac68-061b17574fb8
Industrial CO₂ Capture Report¹ Update

• Cases model capture and compression of a CO₂ source from Industry type
  ◦ Do not model the Industrial Facility
  ◦ Capture/Compression not integrated with Industrial Facility

• Updating report to reflect Fossil Baseline Rev 4 assumptions
  ◦ Updated Financial Assumptions
  ◦ Updated Equipment Quotes
    — Alignment of CO₂ Capture Systems used

• Utilized as a basis for Industrial Capture goals

• Reference for Carbon Capture Retrofit Database
  ◦ Will update CCRD² as well

¹. Cost of Capturing CO2 from Industrial Sources, January 2014, DOE/NETL 2013/1602
   https://netl.doe.gov/projects/files/CostofCapturingCO2fromIndustrialSources_011014.pdf
². Industrial Sources CCRD, April 2019 https://netl.doe.gov/energy-analysis/details?id=6692ea96-fcfa-4ba9-be2c-23647d08a65c
### Industrial Source CO₂ Capture (2014)

<table>
<thead>
<tr>
<th>Industrial Process</th>
<th>Reference Plant Capacity</th>
<th>CO₂ Source Stream</th>
<th>CO₂ to Product Ratio (tonne CO₂/tonne Product)</th>
<th>Source Stream CO₂ Concentration (mol%)</th>
<th>Source Stream CO₂ Partial Pressure (psia)</th>
<th>CO₂ Available for Capture (M tonnes CO₂/year)</th>
<th>Breakeven Cost of Capturing CO₂ ($/tonne CO₂)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>High Purity Sources</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Reference Plant</td>
<td>All U.S. sources</td>
</tr>
<tr>
<td>Ethanol</td>
<td>50 M gal/year</td>
<td>Distillation gas</td>
<td>0.96</td>
<td>100</td>
<td>18.4</td>
<td>0.14</td>
<td>40</td>
</tr>
<tr>
<td>Ammonia</td>
<td>907,000 tonnes/year</td>
<td>Stripping vent</td>
<td>1.9</td>
<td>99</td>
<td>22.8</td>
<td>0.458</td>
<td>6</td>
</tr>
<tr>
<td>Natural Gas Processing</td>
<td>500 MMsct/d</td>
<td>CO₂ vent</td>
<td>N/A¹</td>
<td>99</td>
<td>23.3</td>
<td>0.649</td>
<td>27</td>
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<tr>
<td>Ethylene Oxide</td>
<td>364,500 tonnes/year</td>
<td>AGR product stream</td>
<td>0.33</td>
<td>100</td>
<td>43.5</td>
<td>0.122</td>
<td>1</td>
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<tr>
<td>Coal-to-Liquids (CTL)</td>
<td>50,000 bbl/d</td>
<td>AGR product stream</td>
<td>N/A²</td>
<td>100</td>
<td>265</td>
<td>8.74</td>
<td>-</td>
</tr>
<tr>
<td>Gas-to-Liquids (GTL)</td>
<td>50,000 bbl/d</td>
<td>AGR product stream</td>
<td>N/A²</td>
<td>100</td>
<td>265</td>
<td>1.86</td>
<td>-</td>
</tr>
<tr>
<td><strong>Low Purity Sources</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Reference Plant</td>
<td>All U.S. sources</td>
</tr>
<tr>
<td>Refinery Hydrogen</td>
<td>59,000 tonnes/year</td>
<td>PSA tail gas</td>
<td>10.5</td>
<td>44.5</td>
<td>8.9</td>
<td>0.274</td>
<td>68</td>
</tr>
<tr>
<td>Iron/Steel</td>
<td>2.54 M tonnes/year</td>
<td>Plant Total</td>
<td>2.2</td>
<td>N/A²</td>
<td>N/A²</td>
<td>3.9</td>
<td>2.75</td>
</tr>
<tr>
<td>Cement</td>
<td>992,500 tonnes/year</td>
<td>Kiln Off-gas</td>
<td>1.2</td>
<td>22.4</td>
<td>3.3</td>
<td>1.14</td>
<td>80</td>
</tr>
<tr>
<td>Coal-fired power plants</td>
<td>550 MW</td>
<td>Flue Gas</td>
<td>NA</td>
<td>13.5</td>
<td>2.0</td>
<td>4.13</td>
<td>2,545⁴</td>
</tr>
</tbody>
</table>
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