Cradle-to-Gate Life Cycle Analysis Model for Alternative Sources of Carbon Dioxide

Timothy J. Skone, P.E.
Office of Strategic Energy Analysis and Planning
September 30, 2013
Agenda

Technology Descriptions
Unit Processes
Key Parameters
Co-product Management
Cradle-to-Gate Results
Sensitivities
Technology Descriptions

• CO₂ from Natural Dome
  – CO₂ domes are reservoirs that contain high purity CO₂
  – Existing CO₂ domes include McElmo, Sheep Mountain, Jackson, and Bravo domes in Western U.S.
  – Recovery of CO₂ from natural dome requires construction of a well with a carbon steel casing
  – Natural CO₂ contains water and must be dehydrated prior to compression and pipeline transport

• CO₂ from Natural Gas Processing
  – Unprocessed natural gas contains acid gas, including variable concentrations of CO₂
  – Natural gas processing increases the heating value and reduces the acid gas composition of natural gas
  – Most natural gas processing plants vent natural gas, but at some scales it may be feasible to capture CO₂

• CO₂ from Ammonia Production
  – CO₂ is a co-product of synthetic ammonia
  – Ammonia plants use natural gas as a fuel and feedstock
  – An ammonia plant has two key sources of CO₂, emissions from reforming and emissions from stripping. CO₂ from reforming cannot be easily captured, but acid gas from stripping is 99 percent CO₂ and can be easily captured.
**Unit Processes for CO₂ from Natural Dome**

- **CO₂ well construction adapted from existing unit process for natural gas well construction**
  - Based on environmental impact statement for Kinder Morgan CO₂ extraction sites in Western U.S.
  - Key parameters include well depth, well life, and well production rate
  - Inputs include construction materials (steel and concrete), diesel used by drilling rig, and water used for drilling mud

- **CO₂ well operation accounts for fugitive CO₂ emissions**
  - Valve leakage and other fugitive CO₂ emissions are accounted for by single emission factor, adapted from NETL’s existing unit processes for natural gas extraction
  - Existing natural gas emission factor was adapted according to molecular weights of methane vs. CO₂

- **CO₂ dehydration adapted from existing unit process for natural gas**
  - Reboiler heat and pump power provided by grid electricity instead of natural gas
Key Parameters for CO₂ from Natural Domes

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Low</th>
<th>Expected</th>
<th>High</th>
<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CO₂ Well Construction</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drill speed</td>
<td>1.42E+01</td>
<td>1.78E+01</td>
<td>2.13E+01</td>
<td>m/h</td>
<td>Drilling rate</td>
</tr>
<tr>
<td>Drill depth</td>
<td>1.00E+03</td>
<td>2.08E+03</td>
<td>2.50E+03</td>
<td>m</td>
<td>Well depth</td>
</tr>
<tr>
<td>Drill power</td>
<td>4.47E-01</td>
<td></td>
<td></td>
<td>MW</td>
<td>Power of drilling equipment in brake specific power</td>
</tr>
<tr>
<td>Diesel rate</td>
<td>2.21E+02</td>
<td></td>
<td></td>
<td>kg/MWh</td>
<td>Use rate of diesel; kg of diesel combusted per MWh of brake drilling energy</td>
</tr>
<tr>
<td>Total casing mass</td>
<td>1.03E+05</td>
<td></td>
<td></td>
<td>kg/well</td>
<td>Total mass of carbon steel well casing</td>
</tr>
<tr>
<td>Total concrete mass</td>
<td>1.11E+05</td>
<td></td>
<td></td>
<td>kg/well</td>
<td>Total mass of concrete well casing</td>
</tr>
<tr>
<td>Groundwater proportion</td>
<td>5.00E-01</td>
<td></td>
<td></td>
<td>dimensionless</td>
<td>Fraction of groundwater used during drilling</td>
</tr>
<tr>
<td>Surface water proportion</td>
<td>5.00E-01</td>
<td></td>
<td></td>
<td>dimensionless</td>
<td>Fraction of surface water used during drilling</td>
</tr>
<tr>
<td>Fresh water mass</td>
<td>6.65E+05</td>
<td></td>
<td></td>
<td>kg/well</td>
<td>Fresh water demand for drilling</td>
</tr>
<tr>
<td>Brine water mass</td>
<td>3.11E+05</td>
<td></td>
<td></td>
<td>kg/well</td>
<td>Brine water demand for drilling</td>
</tr>
<tr>
<td><strong>CO₂ Well Operation</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fugitive CO₂</td>
<td>4.64E-06</td>
<td></td>
<td></td>
<td>kg/kg</td>
<td>Fugitive loss of CO₂ from valves, per kg of CO₂ extracted</td>
</tr>
<tr>
<td>Well life</td>
<td>20</td>
<td>25</td>
<td>30</td>
<td>years</td>
<td>Production life of a CO₂ well, used to calculate share of well construction per unit of CO₂ dehydrated</td>
</tr>
<tr>
<td>CO₂ production rate</td>
<td>5.66E+05</td>
<td>8.09E+05</td>
<td>1.05E+06</td>
<td>kg/well-day</td>
<td>Production rate of a CO₂ well, used to calculate share of well construction per unit of CO₂ dehydrated</td>
</tr>
<tr>
<td>Well success rate</td>
<td>0.65</td>
<td>0.70</td>
<td>0.85</td>
<td>dimensionless</td>
<td>Fraction of wells drilled that have economically viable production rates, used to calculate share of well construction per unit of CO₂ dehydrated</td>
</tr>
<tr>
<td><strong>CO₂ Dehydration</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO₂ loss</td>
<td>1.15E-04</td>
<td></td>
<td></td>
<td>kg/kg CO₂</td>
<td>CO₂ emissions released to air during glycol regeneration, in terms of CO₂ treated</td>
</tr>
<tr>
<td>Dehydration Power</td>
<td>1.93E-04</td>
<td></td>
<td></td>
<td>kWh/kg CO₂</td>
<td>Electricity requirements for pumping and heating glycol used for dehydration, in terms of CO₂ treated</td>
</tr>
</tbody>
</table>

- Well construction and operation parameters based on discussions with representatives of Kinder Morgan and comparisons between natural gas and CO₂ well practices
- Dehydration parameters based on comparisons between natural gas and natural CO₂ compositions
Unit Process for CO₂ from Natural Gas Processing

• Adapted from existing acid gas removal process (from NETL’s natural gas model)
  - Unlike existing natural gas model, CO₂ is captured instead of vented
  - Processed natural gas is sent to additional processing steps that are not necessary for CO₂

• Parameters are used to account for variable CO₂ concentrations
  - Production gas contains 1.5 to 70 percent (by mass) CO₂
  - Reference flow of unit process is 1 kg of captured CO₂, so energy and material flows scale according to incoming CO₂ concentration
### Key Parameters for CO₂ from Natural Gas Processing

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Low</th>
<th>Expected</th>
<th>High</th>
<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solvent makeup rate</td>
<td>9.98E-05</td>
<td>1.00E-04</td>
<td>1.01E-04</td>
<td>kg/kg CO₂ captured</td>
<td>Makeup rate of amine solvent for CO₂ recovery, in kg of solvent per kg of CO₂ captured</td>
</tr>
<tr>
<td>Natural gas fuel</td>
<td>6.33E-02</td>
<td>6.64E-02</td>
<td>6.95E-02</td>
<td>kg/kg CO₂ captured</td>
<td>Combusted natural gas input for steam generation per unit of CO₂ captured</td>
</tr>
<tr>
<td>Water input</td>
<td>1.48E-02</td>
<td>1.49E-02</td>
<td>1.50E-02</td>
<td>kg/kg CO₂ captured</td>
<td>Water withdrawal per unit of CO₂ captured</td>
</tr>
<tr>
<td>Surface water share</td>
<td>0.00E+00</td>
<td>5.00E-01</td>
<td>1.00E+00</td>
<td>dimensionless</td>
<td>Share of water withdrawn from surface water sources</td>
</tr>
<tr>
<td>CO₂ input composition</td>
<td>0.8113</td>
<td>0.7882</td>
<td>0.7690</td>
<td>dimensionless</td>
<td>CO₂ fraction of incoming stream</td>
</tr>
<tr>
<td>H₂S input composition</td>
<td>5.00E-03</td>
<td></td>
<td></td>
<td>dimensionless</td>
<td>H₂S fraction of incoming stream</td>
</tr>
<tr>
<td>NGL input composition</td>
<td>1.50E-01</td>
<td></td>
<td></td>
<td>dimensionless</td>
<td>Natural gas liquids (NGL) fraction of incoming stream</td>
</tr>
<tr>
<td>CO₂ pipeline composition</td>
<td>4.70E-03</td>
<td></td>
<td></td>
<td>dimensionless</td>
<td>CO₂ fraction of pipeline natural gas, used to calculate amount of CO₂ removed during processing</td>
</tr>
<tr>
<td>H₂S removal rate</td>
<td>9.80E-01</td>
<td></td>
<td></td>
<td>dimensionless</td>
<td>Removal rate of H₂S</td>
</tr>
</tbody>
</table>

- Solvent makeup and natural gas fuel rates based on variability shown by data sources (FLUOR, 2003; NETL, 2010; NETL, 2011)
- CO₂ composition in incoming gas (i.e., “production gas”) based on characteristics of natural gas wells that capture CO₂ for use in EOR in the Permian Basin
- CO₂ removal rate is a dependent variable, calculated based production gas composition (variable) and pipeline gas composition (0.47% mass CO₂) (NETL, 2012)
Unit Process for CO$_2$ from Ammonia Production

- New unit process, not based on existing NETL unit processes
- Natural gas is feedstock and fuel (coal is a negligible share of ammonia feedstock in the U.S.)
- Ammonia production is a two-step process
  - Step 1: Steam reforming of natural gas to produce carbon monoxide (CO) and hydrogen (H$_2$)
  - Step 2: Catalyzed conversion of hydrogen and nitrogen to ammonia
- Instead of being used for urea production, CO$_2$ is sent to carbon capture, utilization and storage (CCUS)
- Key data sources
  - Energy and feedstock profiles by government-sponsored research (Energetics, 2000; USDA, 2007; Worrell et al., 2000)
  - EPA emission factors for ammonia plants (EPA, 2009)
  - Water use data from European fertilizer industry (EFMA, 2000)
• Total natural gas input is variable
  - Reformer efficiency affects amount of natural gas required for synthesis gas production
  - Intermediate reactions that shift CO to CO₂ also affect amount of natural gas feedstock
  - Extent of heat exchange between ammonia and urea production affects amount of natural gas required for fuel

• Water input is also variable
  - Majority of water input is consumed for steam generation
  - Steam requirements depend on reformer efficiency

• CO₂ production rate is also variable, but is accounted for in the natural gas and water input parameters

• Data limitations prevent parameterization of flows within ammonia plant

### Key Parameters for CO₂ from Ammonia Production

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Low</th>
<th>Expected</th>
<th>High</th>
<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural gas input</td>
<td>7.78E-01</td>
<td>9.30E-01</td>
<td>1.08E+00</td>
<td>kg/kg CO₂ captured</td>
<td>Natural gas input (feedstock and fuel) per unit of CO₂ captured</td>
</tr>
<tr>
<td>Water input</td>
<td>1.10</td>
<td>1.72</td>
<td>2.35</td>
<td>kg/kg CO₂ captured</td>
<td>Water input per unit of CO₂ captured</td>
</tr>
<tr>
<td>Fuel fraction</td>
<td>3.79E-01</td>
<td>4.21E-01</td>
<td>4.64E-01</td>
<td>dimensionless</td>
<td>Fraction of natural gas input used for fuel instead of feedstock</td>
</tr>
</tbody>
</table>
Co-Product Management

• Natural CO$_2$ dome produces only CO$_2$ (no co-products)
• Natural gas processing produces CO$_2$, natural gas, and NGL
  - CO$_2$ cannot be expressed in terms of energy, so energy-based co-product allocation is *not* feasible
  - Mass-based co-product allocation is feasible and is based on masses of produced CO$_2$ and natural gas
  - System expansion is also feasible, but requires consequential assumptions
• Ammonia plant produces CO$_2$ and ammonia
  - CO$_2$ cannot be expressed in terms of energy, so energy-based co-product allocation is *not* feasible
  - Mass-based co-product allocation is feasible and is based on masses of produced CO$_2$ and ammonia
  - System expansion is also feasible, but requires consequential assumptions

These data will be used for attributional LCAs, making mass based allocation the appropriate co-product management method.
Cradle-to-Gate Results for CO₂ from Natural Dome

Steel pipe and land use are significant contributions to total greenhouse gas (GHG) emissions, but the operation of the dehydration process accounts for the majority of GHG emissions.

<table>
<thead>
<tr>
<th>Activity</th>
<th>GHG Emissions (kg CO₂e/kg CO₂)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water Delivery by Truck</td>
<td>1.46E-06</td>
</tr>
<tr>
<td>Steel Pipe Production and Delivery</td>
<td>2.28E-05</td>
</tr>
<tr>
<td>Diesel Production and Delivery</td>
<td>1.14E-06</td>
</tr>
<tr>
<td>Concrete Production and Delivery</td>
<td>2.98E-06</td>
</tr>
<tr>
<td>Well Construction and Installation</td>
<td>7.15E-06</td>
</tr>
<tr>
<td>Grid Electricity</td>
<td>3.94E-06</td>
</tr>
<tr>
<td>Land Use</td>
<td>2.63E-05</td>
</tr>
<tr>
<td>Well Operation</td>
<td>4.64E-06</td>
</tr>
<tr>
<td>Grid Electricity for CO₂ Dehydration</td>
<td>1.39E-04</td>
</tr>
<tr>
<td>CO₂ Dehydration Operations</td>
<td>1.15E-04</td>
</tr>
<tr>
<td>Cradle-to-Gate</td>
<td>3.24E-04</td>
</tr>
</tbody>
</table>
Cradle-to-Gate Results for CO₂ from Natural Gas Processing (Mass Allocation)

Large uncertainty is caused by variability in incoming natural gas composition and its effect on mass allocation factors. As CO₂ composition in incoming gas increases, less natural gas is extracted per unit of CO₂ production, but more processing burdens are allocated to CO₂.
Cradle-to-Gate Results for $\text{CO}_2$ from Ammonia Production (Mass Allocation)

- Uncertainty in GHG emissions from natural gas combustion for steam is driven by uncertainty in total natural gas consumed by ammonia plant and fraction of natural gas used as fuel instead of feedstock.
- $\text{CO}_2$ emissions from reforming process account for most of GHG emissions from ammonia production.

GHG Emissions in 2007 IPCC 100-yr GWP (kg $\text{CO}_2e$/kg $\text{CO}_2$ produced)
• GHG results are sensitive to changes in dehydrator variables (power use and CO₂ loss rate)
• GHG results show an inverse relationship to well production rate, well success rate, and well life – these parameters affect denominator used for apportioning construction and land use burdens
GHG Uncertainty for CO$_2$ from a Natural Dome

Well Construction (Drill Depth - m / Drill Speed - m/hr)
Low 1,000/21.34; Expected 2,076/17.78; High 2,500/14.23

Dehydration Power (kWh)
Low 0.000173; Expected 0.000193; High 0.000212

Electricity Grid
Low US Mix; Baseline ERCOT Mix; High GTSC

GHG Emissions in 2007 IPCC 100-yr GWP
(kg CO$_2$e/kg CO$_2$)

Greatest uncertainty in GHG results is caused by uncertainty in CO$_2$ processing (dehydration)
GHG emissions sensitive to changes in CO₂ composition of incoming gas and steam rates for gas processing.
Due to the high GHG footprint of natural gas extraction, GHG emission sensitivity and uncertainty driven by natural gas input rate.

Data limitations prevent parameterization of other ammonia plant operating characteristics.
Recommendations and Conclusions

• Above results are only from cradle to gate, so they should be used with care

• These new unit processes will allow further LCA modeling of CCUS scenarios
References


