Presentation Outline

• NETL’s Carbon Storage Program
• Introduction of the metrics
• Review of the case study technology
• Application of metrics to the case study technology
• Discussion of metrics interpretation and grouping
NETL Carbon Storage Program

• The Carbon Storage Program contains three key elements:
  – Infrastructure
  – Global Collaborations
  – Core Research and Development:
    • Monitoring, Verification and Accounting (MVA)
    • Geologic Storage
    • Simulation and Risk Assessment
    • CO$_2$ Utilization
NETL Carbon Storage Program

• This analysis supports the CO$_2$ Utilization Focus Area of the DOE-NETL Carbon Storage Program for use in screening current and future utilization technologies:
  – Cement
  – Polycarbonate Plastics
  – Mineralization
  – Enhanced Hydrocarbon Recovery
Screening Metrics

• Developed a set of 12 metrics for use in screening utilization technologies, grouped into 5 categories:

  • **Performance Metrics**:
    - CO$_2$ Utilization Potential
    - CO$_2$ Utilization Efficiency
    - CO$_2$ Utilization Intensity
    - Energy Utilization
    - CO$_2$ Integration Reaction Rate
Screening Metrics

• **Cost Metrics:**
  – Cost per Ton CO₂ utilized
  – Product Marketability
  – Incremental Cost Reduction

• **Emissions Metrics:**
  – CO₂ Emissions Reduction
  – CO₂ Avoided Potential

• **Market Metric:**
  – Product Supply-Demand

• **Safety Metric:**
  – Relative Safety and Environmental Benefits
Case Study: Solidia Technologies

- Technology in development targets (1) production of a Portland Cement substitute, and (2) utilization of CO$_2$ in carbonation chemistry as a binding phase

  - Traditional Portland Cement production:

    $5\text{CaCO}_3 + 2\text{SiO}_2 \rightarrow 3\text{CaO} \cdot \text{SiO}_2 + 2\text{CaO} \cdot \text{SiO}_2 + 5\text{CO}_2$

    Tricalcium Silicate  Dicalcium Silicate

  - Solidia Cement production:

    $\text{CaCO}_3 + \text{SiO}_2 \rightarrow \text{CaSiO}_3 + \text{CO}_2$

    Solidia Cement

- Solidia Cement may also be mined as a naturally occurring mineral (Wollastonite)
## Case Study: Solidia Technologies

### Cement processing comparison:

<table>
<thead>
<tr>
<th></th>
<th>Traditional Portland Cement</th>
<th>Synthetic Solidia Cement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement Kiln Feed</td>
<td>80 Limestone/20 Shale + Clay</td>
<td>50 Limestone/50 Shale + Clay</td>
</tr>
<tr>
<td>Kiln Temperature (°C)</td>
<td>1,500</td>
<td>~ 1,200</td>
</tr>
<tr>
<td>Cement CO₂ Emissions (ton CO₂/ton Cement)</td>
<td>1.2¹</td>
<td>0.0 (natural Wollastonite) 0.77 (synthetic SC)</td>
</tr>
</tbody>
</table>

Case Study: Solidia Technologies

- Utilization of CO$_2$ as a binding phase
  - Activation step for traditional Portland Cement – Hydration
    \[
    2Ca_3SiO_5 + 7H_2O \rightarrow 3CaO \cdot 2SiO_2 \cdot 4H_2O + 3Ca(OH)_2 + 164.5 \text{ Btu}
    \]
  - Activation step for Solidia Cement – Low-Temperature Solidification (LTS)

Solidia Cement

Solidia Concrete

Image used with permission by Solidia
Case Study: Solidia Technologies

• Utilization of CO$_2$ as a binding phase (continued)
  – LTS reaction conditions:
    • Autoclave reaction vessel
    • Temperature: 90°C
    • Pressure: 20 psig
    • Reaction time: 19 hours
    • 65% carbonation – translates to 0.25 tons CO$_2$/ ton cement (utilization)
    • Activation energy: 2.2 kcal/mol (7.87 Btu/mol)
Case Study: Solidia Technologies

• Complete system stages:

- Mixing, Molding, and Finishing stages mirror current concrete practice
- Dry and React stages total 22 hours
Case Study: Solidia Technologies

• Current performance/ path forward:
  – Total cycle emissions:
    • 0.77 (creation) – 0.25 (carbonation) = 0.52 tons CO$_2$ / ton Solidia Concrete (net)
  – Mechanical strength properties compare/ exceed Portland Cement equivalent
  – Structural enhancements: increased thickness, rebar
  – Transition to ‘flue gas-like’ CO$_2$ source
  – Move towards optimized ambient LTS reaction conditions
Calculation Basis

• **Reference case for CO\textsubscript{2} supply:**
  – Supercritical PC plant: 550 MW-net
  – Conventional amine capture technology
  – Available CO\textsubscript{2}: 4.5 M tons/year (85% on-stream factor)
    • Allows for CO\textsubscript{2} available at pressure; no required cost addition
  – Implicit assumption is co-location; no explicit assumption about CO\textsubscript{2} distribution network

• **Production evaluation basis:**
  – 2011 U.S. Portland Cement production of 74.6 M tons
  – Of concrete production: ~80% cast in place, ~20% precast
    • Assumption is 100% of concrete/cement market is accessible
## Application of Metrics to Case Study

<table>
<thead>
<tr>
<th>Performance Metrics</th>
<th>Solidia</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CO₂ Utilization Potential</strong> a – Amount of CO₂ utilized to</td>
<td>413%</td>
</tr>
<tr>
<td>meet product market demand relative to amount of CO₂ emitted</td>
<td></td>
</tr>
<tr>
<td>or captured from the reference</td>
<td></td>
</tr>
<tr>
<td><strong>CO₂ Utilization Efficiency</strong> – Amount of CO₂ utilized per</td>
<td>24.6%</td>
</tr>
<tr>
<td>unit amount of CO₂ fed to the utilization process</td>
<td></td>
</tr>
<tr>
<td><strong>CO₂ Utilization Intensity</strong> – Amount of CO₂ utilized per</td>
<td>0.25 ton CO₂/ton S Cement</td>
</tr>
<tr>
<td>unit amount of the desired product</td>
<td>0.28 ton CO₂/ton S Concrete</td>
</tr>
<tr>
<td><strong>Energy Utilization Metric</strong> – Net amount of energy required</td>
<td>-</td>
</tr>
<tr>
<td>per unit amount of CO₂ utilized (kW-net/(ton CO₂/hr))</td>
<td></td>
</tr>
<tr>
<td><strong>CO₂ Integration Reaction Rate</strong> – Molar rate of CO₂ utilized</td>
<td>-</td>
</tr>
<tr>
<td>per unit of reactor volume (lbₘₒₙ CO₂/gal-yr)</td>
<td></td>
</tr>
</tbody>
</table>

a – Based on CO₂ available from 550 MW-net PC plant
## Application of Metrics to Case Study

<table>
<thead>
<tr>
<th>Cost Metrics</th>
<th>Solidia</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Product Marketability Metric</strong> – Cost to make a unit amount of the desired product relative to the market value of that product</td>
<td>&lt;100%&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td><strong>Incremental Cost Reduction Metric</strong> – Incremental cost reduction of the new utilization process over the traditional process cost (percent)</td>
<td>-</td>
</tr>
<tr>
<td><strong>Cost/Ton CO₂ Utilized</strong> – Annualized capital and operating cost of the utilization system relative to the tons of CO₂ utilized annually ($/ton CO₂)</td>
<td>-</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Emissions Metrics</th>
<th>Solidia</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CO₂ Emission Reduction Metric</strong> – Amount of CO₂ emitted per unit amount of product in the new utilization pathway relative to the traditional pathway</td>
<td>35.8% Cement Only 56.7% for Concrete</td>
</tr>
<tr>
<td><strong>CO₂ Avoided Potential</strong>&lt;sup&gt;b&lt;/sup&gt; – Amount of CO₂ avoided by the proposed technology over the traditional technology relative to the amount of CO₂ emitted from the reference plant</td>
<td>711%</td>
</tr>
</tbody>
</table>

<sup>a</sup> – Approximate, based on discussion with Solidia  
<sup>b</sup> – Based on CO₂ available from 550 MW-net PC plant
# Application of Metrics to Case Study

<table>
<thead>
<tr>
<th>Market Metric</th>
<th>Solidia</th>
</tr>
</thead>
</table>
| **Product Supply-Demand Metric** – Percentage of market that may be satisfied with the proposed technology, considering feedstock or other requirements | 100% $^a$  
60.3% $^b$ |

<table>
<thead>
<tr>
<th>Safety Metric</th>
<th>Solidia</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Relative Safety and Environmental Benefits Metric</strong> – Ranking of the safety of raw materials and processing conditions, including any environmental benefits, of the new utilization pathway relative to those of the traditional pathway (using NFPA category hazard values 0-4; Improved, No Change, or Reduced, over traditional process)</td>
<td>Improved</td>
</tr>
</tbody>
</table>

$^a$ – Based on synthetic SC production  
$^b$ – Based on natural SC production (Wollastonite reserves)
Metric Interpretation and Use

- **Use of metrics is dependent on the end goal of the developer:**
  - Is the scale large and is the goal to maximize CO$_2$ utilization?
    - Focus on Utilization Efficiency/ Potential/ Intensity
  - Is the scale small and is the goal to produce a product capable of offsetting the cost of implementing capture?
    - Focus on Integration Reaction Rate/ Cost per ton CO$_2$ Utilized/ Product Marketability
  - Are the traditional process operating characteristics or chemistry such that improvements in process safety outweigh marginal product economic gains?
    - Focus on Relative Safety and Benefits
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Backup Slides
CO₂ Utilization Potential

\[
\text{CO₂ Utilization Potential (\%)} = \frac{\text{tons CO₂ utilized to meet market demand}}{\text{tons CO₂ available from reference plant}} \times 100
\]

\[
= \frac{18.6 \text{ M tons CO₂ / year utilized}}{4.50 \text{ M tons CO₂ / year available}} \times 100
\]

\[
= 413\%
\]

• Equivalent to 4.1 of the reference plants’ CO₂ streams utilized
CO₂ Utilization Efficiency

\[
\text{CO₂ Utilization Efficiency (\%)} = \frac{\text{tons CO₂ utilized (in - out)}}{\text{tons CO₂ fed to process}} \times 100
\]

\[
= \frac{(145.0 - 109.3) \text{ M tons CO₂ / year utilized}}{145.0 \text{ M tons CO₂ / year fed to process}} \times 100
\]

\[
= 24.6\%
\]

- Based on a single pass of the process (no CO₂ recycle)
CO₂ Utilization Intensity

\[
CO₂ \text{ Utilization Intensity} = \frac{\text{tons CO₂ utilized}}{\text{tons product produced}} \times \% \text{ Carbonation}
\]

\[
= \frac{44.01 \text{ ton CO₂}}{116.16 \text{ ton Solidia Cement}} \times 65\%
\]

\[
= 0.25 \text{ ton CO₂ / ton Solidia Cement}
\]

\[
CO₂ \text{ Utilization Intensity} = \frac{\text{tons CO₂ utilized}}{\text{tons product produced}} \times \% \text{ Carbonation}
\]

\[
= \frac{44.01 \text{ ton CO₂}}{100.08 \text{ ton Solidia Concrete}} \times 65\%
\]

\[
= 0.28 \text{ ton CO₂ / ton Solidia Concrete}
\]
CO₂ Emission Reduction

\[
\text{CO₂ Emission Reduction (\%) } = \left( \frac{\text{tons CO₂ emitted in traditional} - \text{tons CO₂ emitted in new pathway}}{\text{tons CO₂ emitted in traditional pathway}} \right) \times 100
\]

\[
= \left( \frac{1.2 \text{ tons CO₂/ton Portland Cement} - 0.77 \text{ tons CO₂/ton Solidia Cement}}{1.2 \text{ tons CO₂/ton Portland Cement}} \right) \times 100
\]

\[
= 35.8\% \text{ for Solidia Cement}
\]

\[
\text{CO₂ Emission Reduction (\%) } = \left( \frac{\text{tons CO₂ emitted in traditional} - \text{tons CO₂ emitted in new pathway}}{\text{tons CO₂ emitted in traditional pathway}} \right) \times 100
\]

\[
= \left( \frac{1.2 \text{ tons CO₂/ton Portland Cement} - 0.52 \text{ tons CO₂/ton Solidia Concrete}}{1.2 \text{ tons CO₂/ton Portland Cement}} \right) \times 100
\]

\[
= 56.7\% \text{ for Solidia Concrete}
\]
CO₂ Avoided Potential

CO₂ Avoided Potential (%) = \frac{\text{tons of CO₂ avoided to meet market demand}}{\text{tons of CO₂ available from reference plant}} \times 100

= \frac{89.6 \text{ M tons PC CO₂ emitted/year} - 57.5 \text{ M tons SC CO₂ emitted/year}}{4.50 \text{ M tons CO₂ / year available}} \times 100

= 711\%

• Equivalent of 7.1 reference plants’ CO₂ streams avoided
Product Supply-Demand Metric

- Synthetic SC production can meet PC market production, thus Product Supply-Demand Metric is 100% (CO2 supply is not limiting)

\[
\text{Product Supply-Demand Metric (\%) } = \left( \frac{\text{tons per year of product that can be produced}}{\text{tons per year of market demand for that product}} \right) \times 100
\]

\[
= \frac{45.0 \text{ M tons / year of natural SC (Wollastonite)}}{74.6 \text{ M tons / year of PC production}} \times 100
\]

\[
= 60.3\% \text{ based on limited Wollastonite reserves}
\]
Relative Safety and Benefits

- **Example of Relative Safety and Benefits**
  - Traditional Process: Partial Oxidation of Propylene
  - Proposed Process: CO$_2$ Reforming with Ethylene

- **NFPA Feedstock Analysis:**

<table>
<thead>
<tr>
<th>Category</th>
<th>Propylene</th>
<th>Ethylene</th>
</tr>
</thead>
<tbody>
<tr>
<td>Health Risk</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Flammability</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Reactivity</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

- **Cost:**

<table>
<thead>
<tr>
<th></th>
<th>Propylene ($/ton)</th>
<th>Ethylene ($/ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>March (2012)</td>
<td>$1,520$${}^{1}$</td>
<td>$1,010$${}^{1}$</td>
</tr>
<tr>
<td>May (2012)</td>
<td>$1,320$${}^{1}$</td>
<td>$1,069$${}^{1}$</td>
</tr>
</tbody>
</table>

- **Result:** Ethylene feedstock poses higher Health and Reactivity risks, but the nature of the overall proposed process is safer, and ethylene provides an economic benefit as a starting material over propylene.

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Bituminous Baseline Case 12: SC PC

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