Metrics for Screening CO_2 Utilization Processes

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Developing the Technologies and
Infrastructure for CCS

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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 CO_2 utilized
  - Product Marketability
  - Incremental Cost Reduction
- **Emissions Metrics:**
  - CO_2 Emissions Reduction
  - CO_2 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:

$$5CaCO_3 + 2SiO_2 \rightarrow \underset{\text{Tricalcium Silicate}}{3CaO \bullet SiO_2} + \underset{\text{Dicalcium Silicate}}{2CaO \bullet SiO_2} + 5CO_2$$

  - Solidia Cement production:

$$CaCO_3 + SiO_2 \rightarrow \underset{\text{Solidia Cement}}{CaSiO_3} + CO_2$$

    - Solidia Cement may also be mined as a naturally occurring mineral (Wollastonite)

Case Study: Solidia Technologies

- Cement processing comparison:

	Traditional Portland Cement	Synthetic Solidia Cement
Cement Kiln Feed	80 Limestone/20 Shale + Clay	50 Limestone/50 Shale + Clay
Kiln Temperature (°C)	1,500	~ 1,200
Cement CO_2 Emissions (ton CO_2/ton Cement)	1.2[1]	0.0 (natural Wollastonite) 0.77 (synthetic SC)

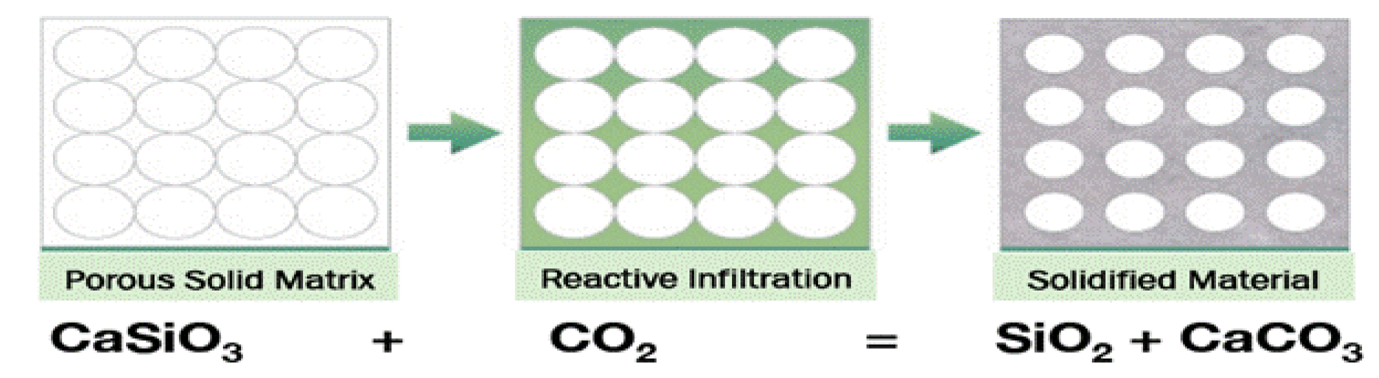
[1]Choate, William T. Energy and Emissions Reduction Opportunities for the Cement Industry. Columbia, MD : 2003.

Case Study: Solidia Technologies

- Utilization of CO_2 as a binding phase
  - Activation step for traditional Portland Cement – Hydration

$$2Ca_3SiO_5 + 7H_2O \rightarrow 3CaO{\bullet}2SiO_2{\bullet}4H_2O + 3Ca(OH)_2 + 164.5\ Btu$$

  - Activation step for Solidia Cement – Low-Temperature Solidification (LTS)



Solidia Cement *Solidia Concrete*

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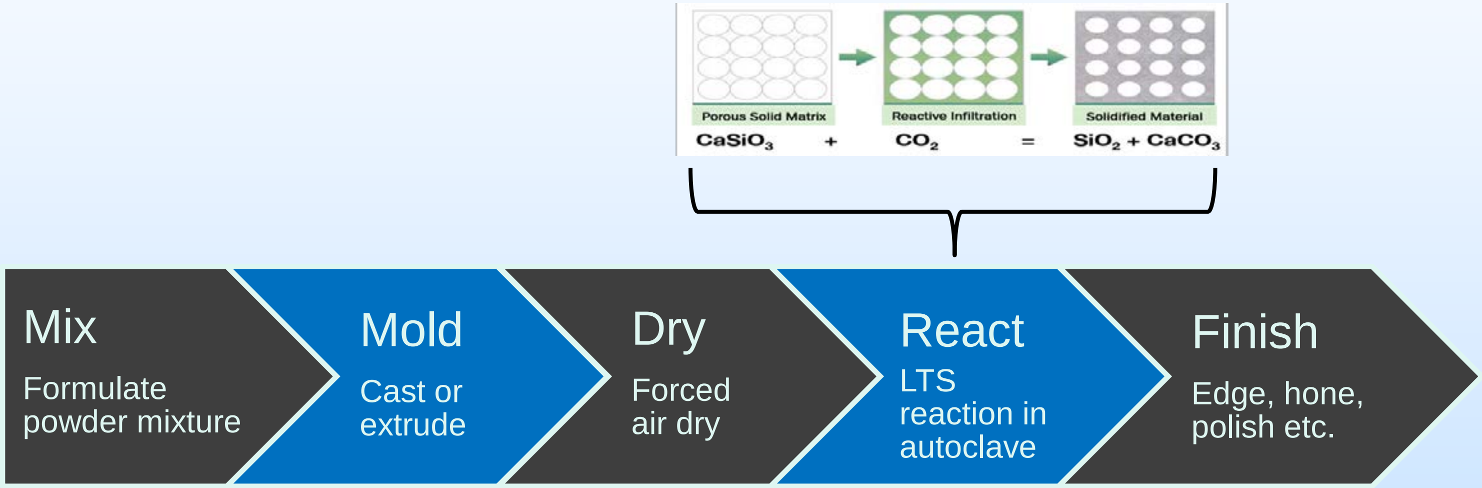
Case Study: Solidia Technologies

- 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:



Images used with permission by Solidia

  - 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_2 supply:**
  - Supercritical PC plant: 550 MW-net
  - Conventional amine capture technology
  - Available CO_2: 4.5 M tons/year (85% on-stream factor)
    - Allows for CO_2 available at pressure; no required cost addition
  - Implicit assumption is co-location; no explicit assumption about CO_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

Performance Metrics	Solidia
CO_2 Utilization Potential [a] – Amount of CO_2 utilized to meet product market demand relative to amount of CO_2 emitted or captured from the reference	413%
CO_2 Utilization Efficiency – Amount of CO_2 utilized per unit amount of CO_2 fed to the utilization process	24.6%
CO_2 Utilization Intensity – Amount of CO_2 utilized per unit amount of the desired product	0.25 ton CO_2/ ton S Cement 0.28 ton CO_2/ ton S Concrete
Energy Utilization Metric – Net amount of energy required per unit amount of CO_2 utilized (kW-net/(ton CO_2/hr))	-
CO_2 Integration Reaction Rate – Molar rate of CO_2 utilized per unit of reactor volume (lb_{mol} CO_2/gal-yr)	-

[a] – Based on CO_2 available from 550 MW-net PC plant

Application of Metrics to Case Study

Cost Metrics	Solidia
Product Marketability Metric – Cost to make a unit amount of the desired product relative to the market value of that product	<100% [a]
Incremental Cost Reduction Metric – Incremental cost reduction of the new utilization process over the traditional process cost (percent)	-
Cost/Ton CO_2 Utilized – Annualized capital and operating cost of the utilization system relative to the tons of CO_2 utilized annually ($/ton CO_2)	-
Emissions Metrics	**Solidia**
CO_2 Emission Reduction Metric – Amount of CO_2 emitted per unit amount of product in the new utilization pathway relative to the traditional pathway	35.8% Cement Only 56.7% for Concrete
CO_2 Avoided Potential [b] – Amount of CO_2 avoided by the proposed technology over the traditional technology relative to the amount of CO_2 emitted from the reference plant	711%

[a] – Approximate, based on discussion with Solidia
[b] – Based on CO_2 available from 550 MW-net PC plant

Application of Metrics to Case Study

Market Metric	Solidia
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]
Safety Metric	**Solidia**
Relative Safety and Environmental Benefits Metric – 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)	Improved

[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

CO_2 Utilization Potential

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

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

$$= 413\%$$

- *Equivalent to 4.1 of the reference plants' CO2 streams utilized*

CO_2 Utilization Efficiency

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

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

$$= 24.6\%$$

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

CO_2 Utilization Intensity

$$CO2\ Utilization\ Intensity = \frac{tons\ CO2\ utilized}{tons\ product\ produced} \times \%\ Carbonation$$

$$= \frac{44.01\ ton\ CO2}{116.16\ ton\ Solidia\ Cement} \times 65\%$$

$$= 0.25\ ton\ CO2\ /\ ton\ Solidia\ Cement$$

$$CO2\ Utilization\ Intensity = \frac{tons\ CO2\ utilized}{tons\ product\ produced} \times \%\ Carbonation$$

$$= \frac{44.01\ ton\ CO2}{100.08\ ton\ Solidia\ Concrete} \times 65\%$$

$$= 0.28\ ton\ CO2\ /\ ton\ Solidia\ Concrete$$

CO_2 Emission Reduction

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

$$= \frac{\text{1.2 tons CO2/ton Portland Cement - 0.77 tons CO2/ton Solidia Cement}}{\text{1.2 tons CO2/ton Portland Cement}} \times 100$$

= *35.8% for Solidia Cement*

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

$$= \frac{\text{1.2 tons CO2/ton Portland Cement - 0.52 tons CO2/ton Solidia Concrete}}{\text{1.2 tons CO2/ton Portland Cement}} \times 100$$

= *56.7% for Solidia Concrete*

CO_2 Avoided Potential

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

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

$$= 711\%$$

- *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)*

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

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

= *60.3% 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:**

Category	Propylene	Ethylene
Health Risk	1	3
Flammability	4	4
Reactivity	1	2

0 – No Risk
4 – Very High Risk

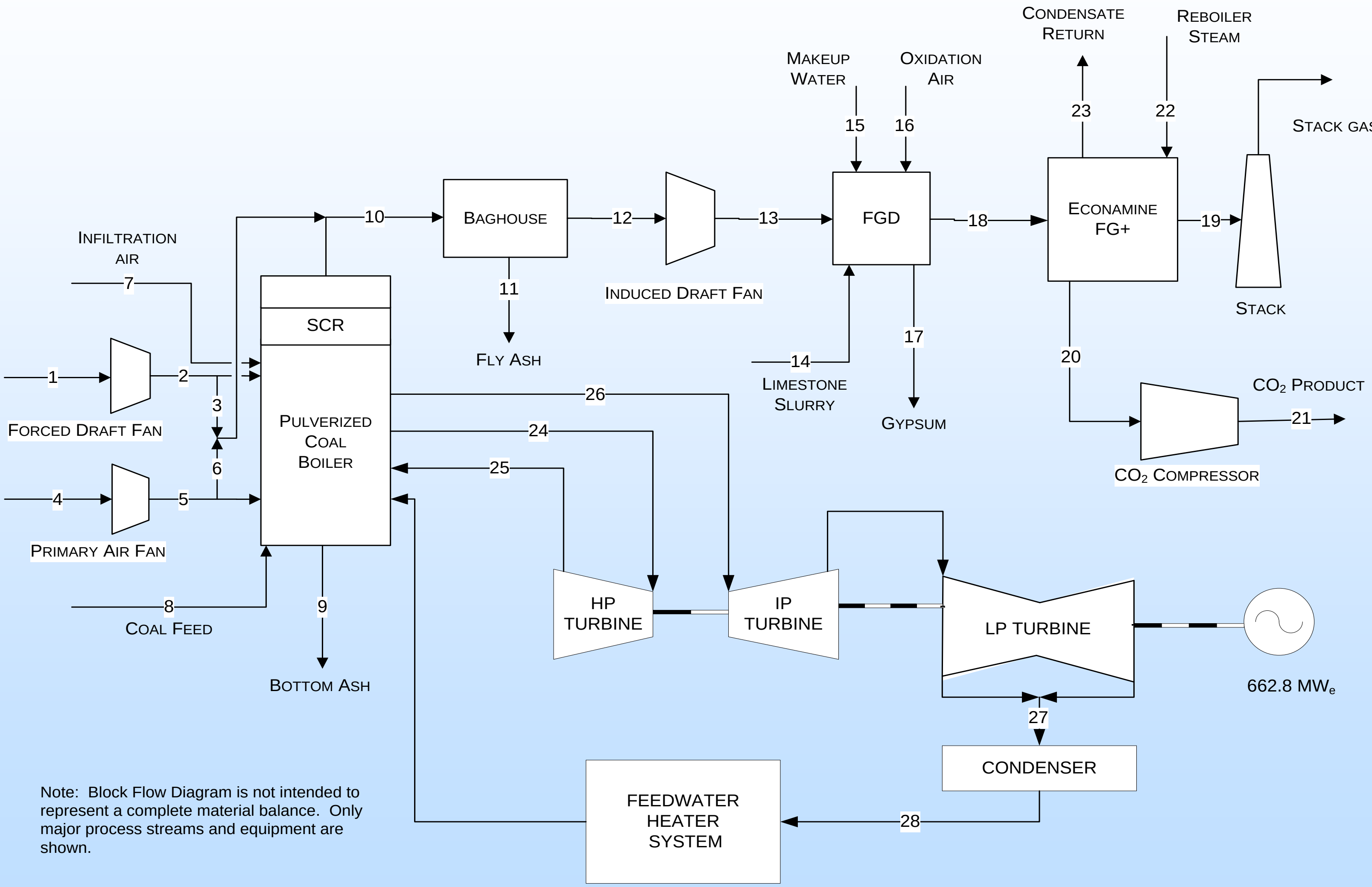
- **Cost:**

	Propylene ($/ton)	Ethylene ($/ton)
March (2012)	$1,520[1]	$1,010[1]
May (2012)	$1,320[1]	$1,069[1]

- **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

[1] Lemos, William. www.ICIS.com. [Online] March 8, 2012. [Cited: May 14, 2012.]

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.