Beneficial Uses for CO₂ Within the State of California

Research Roadmap for Carbon Sequestration Alternatives

Elizabeth Burton, Lawrence Berkeley National Laboratory
Kevin O’Brien, Energy Commercialization, LLC
William Bourcier, Energy Commercialization, LLC
Niall Mateer, University of California, Center for Energy and Environment
John Reed, California Energy Commission

Outline of Presentation

Past, present, future trends

- Background on Energy Commercialization
- One year ago
  - Beneficial Use Analysis
- One year later
  - Results from study / future needs
- One year in the future......

- Emphasis on Identifying Market Impacts
- More than an Academic Study
- Requires Consideration of Technology, Regulatory, & Market Drivers
Energy Commercialization Bio

C-Level execs experienced in energy and reducing operating expenses

- Limited Liability Corporation within the state of California
- Certified small business within the state of California
- Accounting system designed to meet DCAA / DOE requirements
- Experienced working with the Department of Energy (DOE)
- Most of team +30 years experience
- Active in Middle East and Southeast Asia
- Skilled at forming teams to deploy energy technologies
- Project developer for +20 MW projects in US and internationally
- Understand PPA, FIT, and other factors affecting energy deals

Driving and Managing Energy Projects

Energy projects enabled when combining all three components

Finance

Projects

Regulatory

Technology

Skilled at integrating these three components in order to implement projects
Westcarb 2010 : Beneficial Use of CO₂
Based on financial, regulatory, environmental climate in 2010

<table>
<thead>
<tr>
<th>Building Materials</th>
<th>EOR</th>
<th>Algae &amp; Biocconversion</th>
<th>Chemical Conversion</th>
<th>Geothermal</th>
<th>Water-production</th>
<th>CFC Replacement</th>
<th>Consumer</th>
<th>Conventional CCS (aquifers)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geographic Constraints</td>
<td>M</td>
<td>L</td>
<td>H</td>
<td>L</td>
<td>L</td>
<td>L</td>
<td>L</td>
<td>H</td>
</tr>
<tr>
<td>Backend Liability</td>
<td>M</td>
<td>L</td>
<td>M</td>
<td>L</td>
<td>H</td>
<td>M</td>
<td>L</td>
<td>L</td>
</tr>
<tr>
<td>Difficulty of Lifecycle Analysis</td>
<td>L</td>
<td>M</td>
<td>M</td>
<td>M</td>
<td>M</td>
<td>L</td>
<td>L</td>
<td>H</td>
</tr>
<tr>
<td>Sensitivity of Market Economics</td>
<td>L</td>
<td>M</td>
<td>L</td>
<td>M</td>
<td>M</td>
<td>M</td>
<td>M</td>
<td>M</td>
</tr>
</tbody>
</table>

What has Happened Since?
One year later.....

Worldwide trends in CCS projects:
- Modest growth in large-scale integrated projects from 64 in 2009 to 77 in 2010 and now 74 in 2011
- Projects in construction have increased from two in 2009, to four in 2010 and is now at six in 2011
- Projects are moving forward but building a viable business case is proving to be a complex and time consuming process

Pricing carbon:
- Australia carbon tax
- California passes Cap and Trade

"a lot of people didn’t expect us to be here. We surprised a lot of people"

Tim Lincecum, SF Giants
Purpose of Study

**Required by legislation**

- Designed to provide future R&D guidance
- Focus on technologies with potential to assist CA in meeting GHG emissions goals *(per Governor's Executive Order S-3-05 in 2005 and Assembly Bill 32)*
- In-state industrial sources:
  - Refineries, cement plants and natural gas power generators
- Out-of-state sources:
  - Large coal-fired power plants importing power into the state
  - High-carbon fuel stocks for refineries
- Recommended technologies
  - Reach commercialization commensurate with the time frames for California's emissions goals in 2020 and 2050
  - Have the potential to make significant contributions to GHG reduction
Defining Beneficial Use

*Must involve producing a product*

- Technologies that produce a useful product directly from captured anthropogenic CO₂ or in connection with the processes of capture or sequestration of CO₂.
- Capture technologies are *out-of-scope* unless they produce a product as part of the capture process.
- Geologic sequestration not included *except* in cases where something of value, such as additional oil, gas, geothermal heat, or water, is a byproduct.

---

Systematic Process Used

*Enables comparison of a variety of technologies*

1. Define Technology Categories
2. Define Parameters
3. Define Factors for Parameters
4. For Each Technology: Matrix of Parameters and Factors
5. Use Matrix as Basis for Ranking Technologies
Five Key Factors Addressed

*Looks beyond CA border*

1. **State of R&D**
2. Lessons learned and synergy with other efforts
3. Technology barriers and knowledge gaps
4. Role of CO₂ Utilization in Climate Change Mitigation in California
5. Recommendations on Funding through the State of California

---

**Categories of Technologies Examined**

*Casting a wide net for analysis*

<table>
<thead>
<tr>
<th>CATEGORIES</th>
<th>TECHNOLOGY DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ as a working fluid</td>
<td>Enhanced oil recovery (EOR)</td>
</tr>
<tr>
<td>CO₂ as a working fluid</td>
<td>Enhanced gas recovery (EGR)</td>
</tr>
<tr>
<td>CO₂ as a working fluid</td>
<td>Enhanced coal bed methane recovery (ECBM)</td>
</tr>
<tr>
<td>CO₂ as a working fluid</td>
<td>Enhanced geothermal systems (EGS)</td>
</tr>
<tr>
<td>CO₂ for Building Materials Manufacture</td>
<td>Carbonates and other construction materials</td>
</tr>
<tr>
<td>Biochar</td>
<td>Pyrolysis of biomass</td>
</tr>
<tr>
<td>Fuel and Chemical Production</td>
<td>Chemical Conversion</td>
</tr>
<tr>
<td>Fuel and Chemical Production</td>
<td>Biological Conversion</td>
</tr>
<tr>
<td>Power Generation Applications</td>
<td>Super critical CO₂ for Brayton Cycle Turbines</td>
</tr>
<tr>
<td>Power Generation Applications</td>
<td>Working fluid / cushion gas for energy storage</td>
</tr>
<tr>
<td>CO₂ as a Solvent</td>
<td>Supercritical fluid extraction and other food processing applications</td>
</tr>
<tr>
<td>CO₂ as a Solvent</td>
<td>Dry cleaning</td>
</tr>
<tr>
<td>CO₂ in Agriculture and Biomedical Applications</td>
<td>Greenhouse atmosphere additive</td>
</tr>
<tr>
<td>CO₂ in Agriculture and Biomedical Applications</td>
<td>Grain silo fumigant</td>
</tr>
<tr>
<td>CO₂ in Agriculture and Biomedical Applications</td>
<td>Sterilization for biomedical applications</td>
</tr>
<tr>
<td>Miscellaneous Industrial Applications</td>
<td>Fire extinguishers</td>
</tr>
<tr>
<td>Miscellaneous Industrial Applications</td>
<td>Shielding gas for welding</td>
</tr>
<tr>
<td>Miscellaneous Industrial Applications</td>
<td>Refrigeration and heat pump working fluid</td>
</tr>
<tr>
<td>Miscellaneous Industrial Applications</td>
<td>Propellant</td>
</tr>
<tr>
<td>Miscellaneous Industrial Applications</td>
<td>Rubber and plastics processing - blowing agent</td>
</tr>
<tr>
<td>Miscellaneous Industrial Applications</td>
<td>Cleaning during semiconductor fabrication</td>
</tr>
<tr>
<td>Water from displaced aquifer fluids</td>
<td>Water purification</td>
</tr>
<tr>
<td>Water from displaced aquifer fluids</td>
<td>Extraction of Value Added Solids from Water</td>
</tr>
</tbody>
</table>
Methodology Used in Study

*Systems approach focused on the needs of California*

- **Input**
  - \( \text{CO}_2 \) from Stationary sources
  - Component Purity
  - Component Volume/yr
  - MT \( \text{CO}_2 / \text{yr} \)
  - \( \text{CO}_2 \) Purity

- **Process**
  - Process Examined by this Study
  - Opportunities in California

- **Output**
  - Product Produced
  - Product Volume/yr
  - Output: Items other than \( \text{CO}_2 \)

Method to Measure Maturity of Technology

*Many studies done on determining TRL and developing R&D portfolios*

- Technology Readiness Levels (TRLs): scale for assessing the maturity of a particular technology
- Developed by NASA, now wider use in DoD and other agencies
- Viewed as one component of a risk-reduction measure*
- Creates "common language" that facilitates the integration of technologies from universities and research labs (e.g. NRL, ARL)*
- Recent versions include market related risks, e.g. COSYSMO**

*Graettinger, C; S. Garcia, J. Siviy; R. Schenk; P. Syckle, Using the "Technology Readiness Levels" Scale to Support Technology Management in the DoD's ATD/STO Environments*, conducted for Army CECOM, CMU/SEI-2002-SR-027, August 2002

**Valerdi, R; R. Kohl, An Approach to Technology Risk Management, Engineering Systems Division Symposium, MIT, March 2004

Copyright 2011 Energy Commercialization, LLC all rights reserved
Commercialization Pathway

Requires significant capital, talent, and knowledge of stakeholder needs

- Drives type of investor relative to technology maturity
- Field testing begins at pilot scale
- Often failures in transition from lab scale to pilot

Parameters Used in Technology Evaluation

Factors defined to describe each parameter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology Maturity</td>
<td>Technology Readiness Level (TRL)</td>
</tr>
<tr>
<td>Input to Process</td>
<td>Attributes of CO2 required, especially amount of CO2 utilized by process</td>
</tr>
<tr>
<td></td>
<td>Attributes of additional components, especially indicating any water usage</td>
</tr>
<tr>
<td>Output from Process</td>
<td>Attributes of Product Produced</td>
</tr>
<tr>
<td>Time Frame for Commercial Viability</td>
<td>Less than 10 years</td>
</tr>
<tr>
<td></td>
<td>Greater than 10 years</td>
</tr>
<tr>
<td>Environmental impacts</td>
<td>Potential impact on air emissions, disposal of used components, etc.</td>
</tr>
<tr>
<td>Economic Benefit</td>
<td>Job creation / growth of new or existing industries in California</td>
</tr>
<tr>
<td>Federal Investment</td>
<td>Status of previous and existing federal investment in RD&amp;D of technology</td>
</tr>
<tr>
<td>Barriers to deployment</td>
<td>Example: Technology / Regulatory / Economic based factors that limit deployment of technology</td>
</tr>
<tr>
<td>Knowledge gaps</td>
<td>Knowledge or know-how hindering the removal of barriers</td>
</tr>
<tr>
<td>Suppliers</td>
<td>Existing developers / suppliers for the technology</td>
</tr>
</tbody>
</table>
## Sample Characterization of Technologies

*Shown for Working Fluid Category*

<table>
<thead>
<tr>
<th>Technology</th>
<th>Tech. Maturity (Yr)</th>
<th>Estimated Amount of CO₂ Utilized</th>
<th>Attributes of CO₂</th>
<th>Other Components and Their Attributes</th>
<th>Product Produced</th>
<th>Time to Commercialize (≥10 years; &gt;10 years)</th>
<th>Environmental Impacts on California</th>
<th>Projected Economic Benefit to California</th>
<th>Federal Investment in Technology?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enhanced oil recovery (EOR)</td>
<td>9</td>
<td>L</td>
<td>- Sulfur content may enhance EOR, but must maintain pipeline specs for CO₂ transport.</td>
<td>CO₂ Purity Water, surfactants</td>
<td>oil/natural gas</td>
<td>already commercial</td>
<td>Minor (relative to impact of existing oil field)</td>
<td>Jobs &amp; economic stimulus, in vicinity of well field, locally generated fuels, royalties to state</td>
<td>Yes</td>
</tr>
<tr>
<td>Enhanced Gas Recovery (EGR)</td>
<td>3-5</td>
<td>M</td>
<td>Pipeline specs</td>
<td>water</td>
<td>natural gas</td>
<td>&lt;10 years</td>
<td>Minor (relative to impact of existing gas field)</td>
<td>Jobs &amp; economic stimulus, in vicinity of well field, locally generated fuels, royalties to state</td>
<td>Yes</td>
</tr>
<tr>
<td>Coal bed methane recovery (CBMR)</td>
<td>negligible in CA</td>
<td>CO₂ Purity &gt; 90%</td>
<td>Water removed from well to enable methane to move readily</td>
<td>natural gas</td>
<td>&lt;10 years</td>
<td>Coal beds not common in California</td>
<td>Not much direct benefit since coal not a significant resource in California</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Geothermal working fluid (Enhanced Geothermal Systems)</td>
<td>4</td>
<td>M</td>
<td>CO₂ Purity &gt; 80%</td>
<td>Water</td>
<td>electricity</td>
<td>&lt;10 years</td>
<td>Moderate (similar to new geothermal field development)</td>
<td>Electrical power that displaces fossil fuel use, stimulates local economy</td>
<td>Yes</td>
</tr>
</tbody>
</table>

$S$ denotes estimated to be less than 0.5 million metric tons/year  
$M$ denotes estimated to be between 0.5 and 5 million metric tons/year  
$L$ denotes estimated to be greater than 5 million metric tons/year

---

## Five Key Factors Examined

*Looks beyond CA border*

1. State of R&D
2. Lessons learned and synergy with other efforts
3. Technology barriers and knowledge gaps
4. Role of CO₂ Utilization in Climate Change Mitigation in California
5. Recommendations on Funding through the State of California
Summary of Federal Funding

Significant ARRA funding

- Six federal programs accounting for +$300 Million
- Primarily for large scale demonstration projects
- California recipients:
  - Calera Corporation: $20 million;
  - Consortia of research institutions involved in the Fuels from Sunlight Hub: $122 million (Joint Center for Artificial Photosynthesis (JCAP))
- Many projects, especially those involving algae and biodiesel, provide processes for economic conversion of point-source CO₂ emissions

Increasing Flow of Federal Funds into CA

Opportunities exist if CA teams with others

- Provide state funds to meet the requirements for matching funds for federal project
- Encourage teaming of outside institutions and organization with California-based companies, in particular biotechnology companies
- Allow California sites to be used as demonstration facilities for beneficial use technologies
Five Key Factors Examined
*Looks beyond CA border*

1. State of R&D
2. Lessons learned and synergy with other efforts
3. **Technology barriers and knowledge gaps**
4. Role of CO₂ Utilization in Climate Change Mitigation in California
5. Recommendations on Funding through the State of California

Common Barriers & Knowledge Gaps
*Impacts all technology options*

- Need for CO₂ Life Cycle standard
- Monitoring CO₂ Levels, especially for cap and trade considerations
- Permitting, Regulatory, and Legal Hurdles.
Barrier & Gap Analysis

Shown for Working Fluids Category

<table>
<thead>
<tr>
<th>Working fluids</th>
<th>Technical Barriers to Deployment</th>
<th>Regulatory and Other Barriers to Deployment</th>
<th>Knowledge gaps</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enhanced oil recovery (EOR)</td>
<td>- Proximity of wells to CO2 sources - Need for more large scale systems studies - Access to oil fields and economic price for CO2 relative to oil price forecasts - Technological, for monitoring potential CO2 escape - Permitting process in CA exists, but antiquitates storage accounting and Class VI (v.i)</td>
<td>- Monitoring of injected CO2 - Details of long term sequestration</td>
<td>EOR is a mature technology, The amount of CO2 that is truly sequestered is not known. Barriers to deployment in California are mainly the lack of an available CO2 source. None of the existing CO2 pipelines bring CO2 into California. EOR will generate additional installed fuel burning, thus adding to the problem that beneficial re-use is trying to address. DOE-NETL reports estimate 7,537 T C02 could be used between now and 2020 for EOR applications in the U.S. (DOE/NETL, 2012-02) (C.O.E.6)</td>
<td></td>
</tr>
<tr>
<td>Enhanced Gas Recovery (EGR)</td>
<td>- Requires proof-of-concept field studies - Proximity of wells to CO2 sources - Need for more large scale systems studies</td>
<td>Effectiveness of CO2 displacement of crude in field studies</td>
<td>EGR is not a mature technology. While the displacement of OIL by CO2 has been demonstrated as has gas drive in hydrocarbon recovery, field demonstrations are lacking to prove economic efficiency and other economic parameters. Many gas fields in CA are natural oil driven, so it is unclear what residual gas saturations remain and whether they could be enhanced by repressuring with CO2</td>
<td></td>
</tr>
<tr>
<td>Coal bed methane recovery (CBM)</td>
<td>Handled CO2 - Need for long term sequestration</td>
<td>- Monitoring of injected CO2 - Details of long term sequestration</td>
<td>CO2 can be used to displace methane bound to coal surfaces. This technology is analogous to EOR and EGR</td>
<td></td>
</tr>
<tr>
<td>Geothermal (working fluid) Enhanced Geothermal Systems)</td>
<td>- Sophisticated borehole technology - Methods for reservoir optimization - Existing field path fluid flow</td>
<td>Subsurface chemical evolution of CO2 working fluid - CO2 capture flux</td>
<td>CO2 can be used instead of water as a working fluid in geothermal systems. Over long time periods, the CO2 will carbonate the rocks, using the inherent ability of the rocks to form carbonate minerals. This enhances the rate of mineral trapping, a desirable outcome in conventional CCS systems in terms of reducing the rate of long term CO2 confinement</td>
<td></td>
</tr>
</tbody>
</table>

Five Key Factors Examined

Looks beyond CA border

1. State of R&D
2. Lessons learned and synergy with other efforts
3. Technology barriers and knowledge gaps
4. Role of CO2 Utilization in Climate Change Mitigation in California
5. Recommendations on Funding through the State of California
CO₂ Utilization: Many Benefits to CA

*Provides value beyond just GHG reduction*

- Integrated projects where capture provides a CO₂ supply for CO₂ utilization facilities which provide local community benefits such as jobs, while the bulk of the captured stream may still require geologic sequestration
- Replacement of fossil fuel use with CO₂ neutral products
- Potential to address disperse sources which in aggregate may provide significant GHG mitigation volumes

Five Key Factors Examined

*Looks beyond CA border*

1. State of R&D
2. Lessons learned and synergy with other efforts
3. Technology barriers and knowledge gaps
4. Role of CO₂ Utilization in Climate Change Mitigation in California
5. Recommendations on Funding through the State of California
### Ranking Categories

*Important to identify focus*

<table>
<thead>
<tr>
<th>RANK</th>
<th>COMMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>High potential for application in CA (either by volume of CO₂ used or based on other factors that might make the technology important for the state); investment in R&amp;D has potential to lead to a commercially deployable technology in CA to meet 2020 goals</td>
</tr>
<tr>
<td>B</td>
<td>Moderate potential for CA (based on volume or other factors that would make it important to the state); investment in R&amp;D has potential to be commercially deployable to meet 2020 or 2050 goals</td>
</tr>
<tr>
<td>C</td>
<td>Low potential for CA or investment in R&amp;D is high risk with commercialization unlikely to meet 2020 or 2050 goals</td>
</tr>
<tr>
<td>D</td>
<td>Not significant to the state (remove from further consideration)</td>
</tr>
</tbody>
</table>

### Highest Ranking Technologies

*Based on factors listed previously*

<table>
<thead>
<tr>
<th>RANK</th>
<th>TECHNOLOGY</th>
</tr>
</thead>
</table>
| A    | • Biological Conversion  
• Treatment of displaced aquifer fluids  
• EOR and EGR  
• Building materials  
• Working fluids for energy storage |
| B    | • Geothermal working fluid  
• Chemical conversions  
• Working fluids for energy generation |
Key Conclusions from Analysis

Recommendations for future work

- Need to develop a robust lifecycle analysis applicable to all categories
- Need more quantitative means to assess the combination of regional economic impact coupled with environmental impact
- Need more quantitative study of A and B ranked technologies