Reactive CO\textsubscript{2} Capture: Process Integration for the New Carbon Economy

Peter Agbo, Sarah Baker, Todd Deutsch, Doug Kauffman, Josh Schaidle

February 18\textsuperscript{th}-19\textsuperscript{th}, 2020
Marriott Denver West, Golden CO
Workshop Goal and Objectives

**Goal**

Develop a vision for success for reactive CO$_2$ capture within the context of a circular carbon economy and define a strategy for achieving that vision.

**Objectives**

- Develop relationships and bridge gaps between CO$_2$ capture and CO$_2$ utilization
- Identify major technical challenges, knowledge gaps, and barriers to progress
- Define research needs
- Establish metrics for success
Why Reactive Capture?

**Challenge:** High Costs of CO₂ Capture, Transport, and Storage

**Opportunity**
Reactive CO₂ capture could offset costs of storage and enable a circular carbon economy while reducing need for CO₂ transport.

National Petroleum Council, *Meeting the Dual Challenge, A Roadmap to At-Scale Deployment of Carbon Capture, Use, and Storage*, 2019
Definitions and Workshop Scope

**Reactive Capture Definition:** The coupled process of CO$_2$ separation from mixed gas streams and conversion to valuable product(s)

**Can include:**
- Integration of CO$_2$ separation and conversion in one step (e.g., catalyst-coated membrane)
- Integration of separation and conversion in one unit (e.g., regenerating capture media through CO$_2$ conversion during recycle)
- Process intensification in the pathway from CO$_2$ capture to products (e.g., reduced unit ops)

**Workshop Scope:**
- Must form a valuable product, or mixture of products (e.g., more valuable than CO$_2$ loaded capture media)
- The product or mixture of products must be in a more reduced state than CO$_2$ (i.e., conversion of CO$_2$ must involve transfer of reducing equivalents)
- CO$_2$ source agnostic (e.g., atmospheric CO$_2$ and concentrated point sources included)
- Photosynthesis is outside the scope of this workshop
Faradaic Electro-Swing Reactive CO₂ Adsorption

Scientific Approach

• Leverages redox-active species to capture and release CO₂
• CO₂ is captured via the carboxylation of reduced quinones
• CO₂ is released during cell discharge (reversed polarity)
• Cell architecture maximizes the surface area exposed to gas, allowing for ease of stacking of the cells in a parallel passage contactor bed

Significance and Impact

• CO₂ uptake achieved at concentrations as low as 6000 ppm
• CO₂ capacity is independent of the inlet feed concentration
• >90% faradaic efficiency
• Offers an alternative to temperature-swing or pressure-swing adsorption systems
• Opportunity for direct integration with CO₂ conversion
Electrochemical Upgrading of CO$_2$ Capture Solution

Scientific Approach

• CO$_2$ is captured in KOH solution to form (bi)carbonate ions
• Carbonate is fed to the cation conducting side of a bipolar membrane based CO$_2$ electrolyzer
• Protons supplied by the bipolar membrane generate CO$_2$ from carbonate
• CO$_2$ is reduced to CO, at its point of generation from CO$_3^{2-}$, which also regenerates the hydroxide for further capture
• H$_2$ is also produced so pure syngas is the cathode product

Significance and Impact

• Combined capture and conversion demonstration at a relevant current density – 150 mA/cm$^2$
• Energy efficiency ~35%
• Stable operation over 145 hours
• Near 100 % carbon utilization – no need to remove CO$_2$ from product stream
Renewable Methane Production

Scientific Approach

- Utilize excess electricity production for the electrolysis of water to $H_2$ and $O_2$
- Optimized strain of methanogenic archaea to perform methanation under industrial conditions
- 125 kW PEM electrolyzer feeds 2.5 kg $H_2$/h, continuously producing 4.1 scfm $CH_4$
- 98% carbon efficiency of $CO_2$ to $CH_4$
- Post-processing for pipeline quality natural gas

Significance and Impact

- Potential long-term storage strategy via conversion of electricity and $CO_2$ to $CH_4$
- High efficiency $CO_2$ capture and conversion strategy
- Demonstrated route to renewable methane
- Large market and NG-grid to absorb curtailed electricity

\[4H_2 + CO_2 \rightarrow CH_4 + 2H_2O + \text{Heat}\]
CO₂ to Methanol via KOH/Ethylene Glycol

Scientific Approach
- CO₂ is captured in a mixture of KOH and ethylene glycol
- Captured CO₂ is hydrogenated into methanol at mild temperatures using H₂ and a Ru-based catalyst
- Quantitative methanol yields after 20 hours under 70 bar H₂ and 140 °C
- Lower operating temperatures also possible
- Regeneration of capture solvent allows multiple capture/conversion cycles
- Demonstrated potential for direct air reactive capture

Significance and Impact
Clear potential for integrating direct air capture with production of a carbon neutral commodity chemical
Carbon Nanotubes via Molten Carbonate Electrolyzers

Scientific Approach

• Molten carbonate electrolyzer
• Governing reactions:
  (1) \( \text{CO}_2 (g) + \text{Li}_2\text{O} \rightarrow \text{Li}_2\text{CO}_3 \)
  (2) \( \text{Li}_2\text{CO}_3 \rightarrow \text{C} (s) + \text{Li}_2\text{O} + \text{O}_2 (g) \)
  \( \text{Net} \quad \text{CO}_2 \rightarrow \text{C} + \text{O}_2 \)
• Control carbon nanofiber morphology via current density, electrolyte (Li-K-Na), and electrolytic temperature

Significance and Impact

• Potential for high coulombic and carbon efficiencies if \( \text{Li}_2\text{CO}_3 \) is not consumed during the reaction and is continuously regenerated from \( \text{CO}_2 \)
• High-value product
• Leverages atmospheric \( \text{CO}_2 \)
<table>
<thead>
<tr>
<th>Time</th>
<th>Event</th>
<th>February 18th, 2020</th>
<th>February 19th, 2020</th>
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</thead>
<tbody>
<tr>
<td>1:00pm</td>
<td>Meeting Kick-off</td>
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<td>7:00-8:00am</td>
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<tr>
<td>1:15-2:00pm</td>
<td>Bill Tumas (NREL) and Roger Aines (LLNL)</td>
<td>8:00-8:30am</td>
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<tr>
<td>2:05-2:50pm</td>
<td>Sean Simpson (Lanzatech)</td>
<td>8:35-9:05am</td>
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<td>2:50-3:20pm</td>
<td>Break</td>
<td>9:05-9:20am</td>
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<td>3:20-5:00pm</td>
<td>Panel Discussion</td>
<td>9:20-9:50am</td>
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<td></td>
<td>• Ian Rowe (Bioenergy Technologies Office)</td>
<td>9:55-10:25am</td>
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<td>• Lynn Brickett (Office of Fossil Energy)</td>
<td>10:25-10:45am</td>
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<td>• Paul Kenis (University of Illinois)</td>
<td>10:45-12:00pm</td>
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<td></td>
<td>• Todd Wilke (Carbon Engineering)</td>
<td>12:00-1:00pm</td>
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<td>• Bill Tumas (NREL)</td>
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<td>• Roger Aines (LLNL)</td>
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<tr>
<td>5:00-5:30pm*</td>
<td>Break (Poster presenters set up posters)</td>
<td>3:15-4:00pm</td>
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<td>5:30-8:00pm</td>
<td>Reception and Poster Session</td>
<td>4:00-4:15pm</td>
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<td></td>
<td>What does success look like?</td>
<td>How do we achieve success?</td>
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*All moderators please meet in the Golden Ballroom at 5pm today to discuss roles and responsibilities*
Ground Rules

• All ideas/thoughts are welcome – give everyone a chance to contribute
• Keep an open mind
• Please step out if you need to take a call
• Think big, check your baggage at the door, and have fun
Thank You!

• Speakers and Panelists
• All attendees
• Linda Stolmack
• Co-Organizers
• Department of Energy
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