Economic and Environmental Sustainability of an Integrated Direct Air Capture System with Advanced Algal Biofuel Production

Kylee Harris1*, Eric C. D. Tan1, Valerie M. Thomas2, Jaden Johnston2, Shavonn D’Souza2, Christopher W. Jones2, Eric W. Ping3, Miles Sakwa-Novak3, Yanhui Yuan3, Ron Chance3

1National Renewable Energy Laboratory, Golden, CO
2Georgia Institute of Technology, Atlanta, GA
3Global Thermostat LLC, Commerce City, CO

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Background and Motivation

- Promote the decarbonization of the atmosphere
- Decouple algae production facilities from anthropogenic CO₂ sources
- Identify key economic drivers
- Minimize cost and greenhouse gas emissions through process integration and optimization
Direct Air Capture (DAC) Technology

- Modular design

- Low temperature CO$_2$ recovery
  - Amine-coated structured monolith
  - A novel temperature/vacuum swing adsorption (TVSA) process

- No point source CO$_2$ required

DOE BETO 2019 Project Peer Review, Denver, CO. “Direct Air Capture of CO2 and Delivery to Photobioreactors for Algal Biofuel Production” https://www.energy.gov/sites/prod/files/2019/03/f60/BETOPeerReview-Program2019%20%28003%29_G.pdf
Algenol Photobioreactor (PBR) Technology

- 2,000-acre model for biorefinery
- 16MM gal ethanol/year
  - 20 tonnes/hr CO₂ required
- Genetically engineered cyanobacteria for ethanol production
- 70% of photosynthetically-fixed carbon diverted to ethanol pathway
- 85% CO₂ conversion to ethanol or biomass

Techno-Economic Analysis (TEA) Methodology

- Assumed nth-plant economics
- Processes modeled in Aspen Plus using experimental data, literature data, and vendor performance information
- Capital and operating costs acquired from quoted information by Algenol and Global Thermostat, Aspen Capital Cost Estimator V10 (ACCE), and NREL internal costing libraries
- TEA material and energy flows used to generate life-cycle inventory (LCI) for LCA
Key Considerations:

- 2,000-acre algae farm can be divided into uniform subplots
- Heat and mass integration is critical for reducing energy requirements and process costs
- Each processing step can be viewed as individual modules, which can be scaled and relocated as needed
- Previous work determined large-scale circulation of dilute flue gases is not economically viable
- Smaller, modularized units will not benefit from economies of scale
## TEA Results

<table>
<thead>
<tr>
<th>DAC Operating Hours</th>
<th>12</th>
<th>24</th>
<th>12</th>
<th>24</th>
<th>12</th>
<th>24</th>
<th>12</th>
<th>24</th>
<th>12</th>
<th>24</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ Compressed/Stored</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Flue Gas CO₂ Utilized</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Baseline</th>
<th>Option 0</th>
<th>Option 1</th>
<th>Option 2a</th>
<th>Option 2b</th>
<th>Option 2a – nth plant DAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>MFSP ($/gal EtOH)</td>
<td>$10.68</td>
<td>$9.33</td>
<td>$9.10</td>
<td>$8.78</td>
<td>$8.93</td>
<td>$8.25</td>
</tr>
<tr>
<td>%MFSP Reduction</td>
<td>-</td>
<td>12.6%</td>
<td>14.8%</td>
<td>17.8%</td>
<td>16.4%</td>
<td>22.8%</td>
</tr>
<tr>
<td>EtOH annual production (MMGal/yr)</td>
<td>16.0</td>
<td>16.0</td>
<td>16.0</td>
<td>16.0</td>
<td>16.0</td>
<td>16.0</td>
</tr>
<tr>
<td>FCI (MM$)</td>
<td>860.5</td>
<td>724.1</td>
<td>695.2</td>
<td>694.6</td>
<td>719.9</td>
<td>654.3</td>
</tr>
<tr>
<td>Total operating costs (MM$/yr)</td>
<td>53.6</td>
<td>51.5</td>
<td>51.8</td>
<td>47.2</td>
<td>45.7</td>
<td>44.8</td>
</tr>
<tr>
<td>CO₂ from DAC (tonne/hr)</td>
<td>40.0</td>
<td>20.0</td>
<td>17.9</td>
<td>12.9</td>
<td>18.9</td>
<td>14.9</td>
</tr>
<tr>
<td>DAC operating hours (hr/day)</td>
<td>12</td>
<td>24</td>
<td>24</td>
<td>24</td>
<td>12</td>
<td>24</td>
</tr>
<tr>
<td>Percent of total CO₂ demand from DAC</td>
<td>100%</td>
<td>100%</td>
<td>90%</td>
<td>64%</td>
<td>47%</td>
<td>75%</td>
</tr>
<tr>
<td>Weighted CO₂ cost ($/tonne)*</td>
<td>$407</td>
<td>$275</td>
<td>$232</td>
<td>$226</td>
<td>$275</td>
<td>$165</td>
</tr>
</tbody>
</table>

*Assumes CO₂ from flue gas is free
TEA Results

Reductions in MFSP attributed to two primary process considerations:

1) CO₂ storage at night reduces the capital expenses associated with DAC (increasing on-stream time)
2) Distributed DAC scenarios (2a and 2b) make use of boiler and DAC CHP flue gas CO₂ (free)
## Carbon Footprint: Need $\frac{CO_{2e} \text{emitted}}{CO_{2c} \text{aptured}} < 1$

<table>
<thead>
<tr>
<th>Lifecycle GHG Emissions (g CO$_2$e/MJ EtOH)$^1$</th>
<th>Baseline</th>
<th>Option 0</th>
<th>Option 1</th>
<th>Option 2A</th>
<th>Option 2A (nth)</th>
<th>Option 2B</th>
</tr>
</thead>
<tbody>
<tr>
<td>108</td>
<td>104</td>
<td>105</td>
<td></td>
<td>73.8</td>
<td>47.6</td>
<td>71.0</td>
</tr>
</tbody>
</table>

Gasoline: **91.3** g CO$_2$e/MJ  
US Standard$^2$ → Biofuel: **45.6** g CO$_2$e/MJ

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Direct air capture technology eliminates the constraint of co-locating algal biofuel production with point-source CO₂.
- Localized utilization of captured CO₂ versus long distance CO₂ pipelines
- Ambient air contains fewer contaminants than flue gas

Heat and mass integration decreases plant expenses via reduced energy consumption.
- Flue gas utilization reduces DAC demand and reduced overall cost through use of “free carbon”
- High capital utilization (process uptime) is crucial for minimizing DAC costs

Further process optimization is being pursued.
- Goal to reduce waste heat and CO₂ generation though further integration
- Assessing increased oxidative stability and lifetime of monoliths to lower operating expenses and increase regeneration capabilities
Questions?

Speaker Information
Kylee Harris
Kylee.Harris@nrel.gov

DOE’s Bioenergy Technologies Office (BETO)
http://www.eere.energy.gov/biomass

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