Improving the Economic Viability of Biological CO₂ Utilization by Improved Algae Productivity & Integration with Wastewater Treatment

Cooperative Agreement No: DE-FE0030822

CO₂ Capture Technology Project Review Meeting
August 17, 2018

Illinois Sustainable Technology Center
Basic Project Information

- Title: *Improving the Economic Viability of Biological Utilization of Coal Power Plant CO₂ by Improved Algae Productivity & Integration w/ Wastewater Treatment*
  - DOE Program Manager: Andy Aurelio
  - Lead Organization: University of Illinois - Illinois Sustainable Technology Center
  - PI: Lance Schideman, PhD, PE
  - Major Collaborating Organization: Helios-NRG
  - Project Cooperative Agreement Number: DE-FE0030822

- DOE Funding Program DE-FOA-0001622: *Applications for Technologies Directed at Utilizing Carbon Dioxide from Coal Fired Power Plants*
  - Total Project Value: $1,249,873  Government: $999,536  Cost Share: $250,337
  - Budget Period 1 Total Value: $414,242  Government: $331,394  Cost Share: $82,848

  - Currently in Budget Period 1 (BP1) - October 1, 2017 – September 30, 2018
Major Project Objectives

• **Improve Algal Productivity & CO₂ Capture by Improved Bioreactor Design & Oper.**
  • Proprietary reactor design and algal strains grown on simulated flue gas with key contaminants added
  • End of project performance goals
    • 35 g/m²-day biomass productivity
    • 70% carbon capture efficiency

• **Reduce Net Costs and Energy Inputs for Producing Algal Products**
  • Integrate use of low-cost or negative-cost wastewater nutrient inputs
    • Large quantity of sustainable nutrients available
  • Develop low-energy forward osmosis dewatering
  • Membrane separation & recycle of aqueous byproducts from hydrothermal biofuel processes
  • Algal biomass for animal feed
    • Large-volume stable markets with potential for higher net value than biofuels
    • Sanitary sewer distribution of flue gas

• **Evaluate Life-cycle and Techno-economic Impacts of Proposed System**
Objectives in Context of Block Flow Diagram

- Improve Algae Productivity & CO₂ Capture by Improved Bioreactors & Acclimation
- Reduce Net Cost of Algae Production by Integrating CO₂ Capture with Wastewater Treatment
- Increase Value of Algal Biomass by Developing Animal Feed Products
- Reduce Dewatering Energy Using Forward Osmosis
- Reduce Cost of HTL Aq. Product Treatment via Membrane Conc. & Recycling

LCA & TEA of Proposed System
• Task 1- Project Management
• Task 2- Demonstrate Stable Algae Cultivation w/ Simulated Flue Gas
• Task 3- Demonstrate Stable Algae Cultivation w/ Wastewater Nutrients
• Task 4- Optimize \( \text{CO}_2 \) Capture Efficiency in the Algae Cultivation Process
• Task 5- Evaluate Novel Algae Dewatering Processes (forward osmosis)
• Task 6- Characterize algal biomass for HTL and animal feed applications
• Task 7- Demonstrate ability to concentrate & recycle HTL aqueous phase
• Task 8- Evaluate the potential of sewer network flue gas distribution
• Tasks 9- Techno-Economic Analysis
• Tasks 10- Techno-Economic Analysis
Project Organizational Chart

PRIME CONTRACTOR
University of Illinois (UI)

Responsibilities:
• Project Management
• HTL Process improvements
• Algae biomass characterization,
• Testing for animal feed applications
• Evaluation of sewer system for flue gas transport
• Techno-economic and Life-cycle analysis for dewatering and conversion processes

INDUSTRIAL ADVISORY BOARD
Managers and Design Consultants from Power and Wastewater Industries

Responsibilities:
• Advise on current industry drivers and concerns
• Review plans for integration with existing infrastructure facilities
• Review and comment on project results

SUBAWARDEE
Helios-NRG, LLC

Responsibilities:
• Algae cultivation with flue gas
• Algae cultivation with wastewater
• Commercialization Strategy
• Techno-economic and Life-cycle analysis for algae cultivation and harvesting processes

• Industrial Advisory Board Members
  • Springfield City Water, Power & Light
    • 578 MW coal-fired steam turbine generators
  • Urbana-Champaign Sanitary District
    • 40 MGD Wastewater Treatment Plant Capacity
  • Fehr-Graham Engineering
    • Wastewater Design Consultant
Baseline Algae Elemental Mass Composition - 36%C, 7%H, 50%O, 6%N, 1%P

Est. Wastewater Treatment Value of Algal Nutrient Uptake: \( (0.06 \times 4.26 + 0.01 \times 8.57) \times 2000 = \$680/\text{ton} \)

What is the Value of Wastewater Nutrient Removal?


<table>
<thead>
<tr>
<th>Cost Categories</th>
<th>2015 Current State of Technology w/ Algae Productivity of 8.5 g/m²/day</th>
<th>2022 DOE Projected Design Case w/ Algae Productivity of 25 g/m²/day</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(Project Economic Impacts)</td>
</tr>
<tr>
<td>Algal Biomass Production Costs ($/ton)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ponds &amp; Inoculum</td>
<td>$ 1,359</td>
<td>$ 289 (Raceway pond mods + $44)</td>
</tr>
<tr>
<td>CO₂ Supply</td>
<td>$ 99</td>
<td>$ 97 (Carbon capture credit - $60)</td>
</tr>
<tr>
<td>Dewatering Operations</td>
<td>$ 82</td>
<td>$ 52</td>
</tr>
<tr>
<td>Nutrient Supply</td>
<td>$ 25</td>
<td>$ 24 (WW credit -$680)</td>
</tr>
<tr>
<td>Other Costs</td>
<td>$ 76</td>
<td>$ 32</td>
</tr>
<tr>
<td>TOTAL Algae Biomass Prod</td>
<td>$ 1,641 /dry ton (DT)</td>
<td>$ 494 /DT (-$202/DT)</td>
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<tr>
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<tr>
<td>Algal Biofuel Production Costs ($/gge)</td>
<td></td>
<td></td>
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<tr>
<td>Algae Biomass Supply</td>
<td>$ 15.15</td>
<td>$ 3.18 (Sum of above -$1.28)</td>
</tr>
<tr>
<td>Hydrothermal Liquefaction Conv.</td>
<td>$ 1.18</td>
<td>$ 0.49</td>
</tr>
<tr>
<td>Bio-oil Upgradation/Finishing</td>
<td>$ 0.44</td>
<td>$ 0.31</td>
</tr>
<tr>
<td>Aqueous product post-treatment</td>
<td>$ 1.54</td>
<td>$ 0.57 (Conc/recycle aq prod. $0.28)</td>
</tr>
<tr>
<td>Balance of Plant</td>
<td>$ 0.29</td>
<td>$ 0.17</td>
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<tr>
<td>TOTAL Biofuel Production Costs</td>
<td>$ 18.60 / gal gasoline equiv (gge)</td>
<td>$ 4.72/gge (-$0.03/gge)</td>
</tr>
</tbody>
</table>
Impact of flue gas contaminants on algae growth

Simulated post-FGD flue gas (all with 12% CO2)

Normalized Growth Rate (%)

Species: H-1903

- Control
- Sox + Nox
- Cu + Cr
- Cu, Cr, As, Hg, Se
Impact of flue gas contaminants on algae growth

Simulated post-FGD flue gas (all with 12% CO2)
### Algae Heavy Metal Content after Combined Heavy Metal Tests

Compared with Animal Feed Maximum Tolerable Level (MTL) (National Research Council, 2005)

<table>
<thead>
<tr>
<th>Minerals</th>
<th>H-1903 2 HM (ppm)</th>
<th>H-1903 5 HM (ppm)</th>
<th>Poultry Feed MTL (ppm)</th>
<th>Swine Feed MTL (ppm)</th>
<th>Cattle Feed MTL (ppm)</th>
<th>Fish Feed MTL (ppm)</th>
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<tbody>
<tr>
<td>As</td>
<td>2.18</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>5</td>
</tr>
<tr>
<td>Cd</td>
<td>स्प्य</td>
<td>स्प्य</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Cr</td>
<td>2.93</td>
<td>1.16</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>3,000* as CrO</td>
</tr>
<tr>
<td>Co</td>
<td>स्प्य</td>
<td>स्प्य</td>
<td>25</td>
<td>100</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>Cu</td>
<td>64.8</td>
<td>46.6</td>
<td>250</td>
<td>250</td>
<td>40</td>
<td>100</td>
</tr>
<tr>
<td>Pb</td>
<td>स्प्य</td>
<td>स्प्य</td>
<td>10</td>
<td>10</td>
<td>100</td>
<td>10</td>
</tr>
<tr>
<td>Ni</td>
<td>स्प्य</td>
<td>स्प्य</td>
<td>250</td>
<td>250</td>
<td>100</td>
<td>50</td>
</tr>
<tr>
<td>Se</td>
<td>7.7</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>2</td>
<td></td>
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<tr>
<td>Zn</td>
<td>10.3</td>
<td>11.3</td>
<td>500</td>
<td>1000</td>
<td>500</td>
<td>250</td>
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</tbody>
</table>

- **Algal biomass over accumulated Cu, Se which could limit certain animal feed applications without management or mitigation**
Comparison of Wastewaters Used for Algae Cultivation

<table>
<thead>
<tr>
<th>Sample Type &amp; Treatments</th>
<th>TSS (mg/L)</th>
<th>COD (mg/L)</th>
<th>NH3-N (mg/L)</th>
<th>NO3-N (mg/L)</th>
<th>Total N (mg/L)</th>
<th>Total P (mg/L)</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muni-WW Centrifuge Centrate</td>
<td>n/a</td>
<td>260 ±12</td>
<td>1021 ±8</td>
<td>22 ±17</td>
<td>1133 ±76</td>
<td>274 ±2</td>
<td>7.7</td>
</tr>
<tr>
<td>HTL Aq Product</td>
<td>Filtered &amp; Autoclaved</td>
<td>44,177 ±326</td>
<td>7,206 ±66</td>
<td>360</td>
<td>10,944 ±1,237</td>
<td>2,108 ±7</td>
<td>5.6</td>
</tr>
</tbody>
</table>

- HTL aq product was significantly stronger than municipal wastewater dewatering centrate
  - Higher organics (~100x)
  - Higher nutrients (~10x)
  - HTL aq product has nitrogen-substituted organics and phenolics that have been shown to have inhibitory effects on microbial growth including algae
Impact of wastewater nutrient replacement on algae growth

Lower-strength centrate wastewater from biosolids dewatering

Species: H-1903

- Control
- 100% Comm
- Reduced 16% Comm
- 16% Comm + 100% Waste water
Impact of wastewater nutrient replacement on algae growth

Higher-strength HTL aq wastewater from biofuel production

Species: H-0322

- Control 100% Comm
- 70% Comm + 30% HTL Aq
- 40% Comm + 60% HTL Aq
- 5% Comm + 95% HTL Aq
Weekly Avg. Productivity With Flue Gas & Wastewater Inputs

Species: H-1903

- Sox + Nox
- Cu, Cr, As, Hg, Se
- WW Nutrient Replace
Weekly Avg. Productivity With Flue Gas & Wastewater Inputs

Species: H-0322

- Sox + Nox
- Cu, Cr, As, Hg, Se
- WW Nutrient Replace

% of Target Productivity

0% 20% 40% 60% 80% 100% 120%
## Project Milestones for Budget Period 1

<table>
<thead>
<tr>
<th>Budget Period</th>
<th>Task #</th>
<th>Milestone #</th>
<th>Description</th>
<th>Planned Completion Date</th>
<th>Actual Completion Date</th>
<th>Verification Method</th>
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<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>T1.1</td>
<td>Kickoff Meeting</td>
<td>Dec. 2017</td>
<td>Dec. 2017</td>
<td>Presentation file</td>
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<td>1</td>
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<td>T3.1</td>
<td>Stable Algae Growth with wastewater nutrients</td>
<td>Sept. 2018</td>
<td></td>
<td>BP1 Annual Progress Report</td>
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<td></td>
<td>G/N-1</td>
<td></td>
<td>Algal Productivity with Simulated Flue Gas &gt; 25 g/m²/d</td>
<td>Sept. 2018</td>
<td></td>
<td>DOE Annual Review</td>
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<tr>
<td>Decision Point</td>
<td>Date</td>
<td>Success Criteria</td>
<td></td>
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<td>----------------------------------------------------------------------------------</td>
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<td></td>
</tr>
<tr>
<td>G/N-1 Go/No-Go Budget Period 1</td>
<td>9/30/2018</td>
<td>Algal Productivity &gt; 25 g/m²/d (weekly average) with Simulated Flue gas containing 12% CO2, SOX, NOX and representative levels of heavy metals Hg, Se, As, Cu and Cr</td>
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<tr>
<td>G/N-2 Go/No-Go Budget Period 2</td>
<td>9/30/2019</td>
<td>Algal Productivity &gt; 25 g/m²/d (weekly average) and &gt;70% CO2 capture with Simulated Flue gas containing 12% CO2, SOX, NOX and representative levels of heavy metals Hg, Se, As, Cu and Cr</td>
<td></td>
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<tr>
<td>G/N-3 Go/No-Go Budget Period 3</td>
<td>9/30/2020</td>
<td>Integrated Application of Project Technologies w/ Projected Cost of Algal Biomass &lt; $470 /dry ton</td>
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</tbody>
</table>
## Technical Risks & Potential Mitigation Strategies

<table>
<thead>
<tr>
<th>Description of Risk</th>
<th>Probability</th>
<th>Impact</th>
<th>Risk Management- Mitigation and Response Strategies</th>
</tr>
</thead>
</table>
| Algae growth is inhibited by contaminants in post-FGD flue gas (SO\textsubscript{x}, NO\textsubscript{x}, metals) | Medium      | Medium to High   | • Use adsorbents in algal culture to sequester problem contaminants  
• Problem contaminants can be removed from the simulated flue gas  
• For future applications flue gas pre-treatment may be required                                                                                                                                  |
| Algae growth is inhibited by contaminants in nutrient-rich wastewater liquids        | Low         | Medium to High   | • Use adsorbents to sequester problem contaminants  
• Wastewater filtrate can be pre-treated to remove problem contam.  
• Wastewater filtrate use for algae cultivation can reduced/eliminated                                                                                                                      |
| Algal uptake of CO\textsubscript{2} is not fast enough for capture goal (70-90% removal in 3 stages) | Low         | Low             | • Provide fine bubble diffusers if it is a physical mass transfer limitation  
• Add stages if it is a biological limitation                                                                                                                                                    |
| Forward osmosis dewatering flux is too low to facilitate cost-effective applications  | Low         | Medium          | • Pre-treat algal biomass with ultrasound to open cells and reduce resistance to water diffusion through the cell walls  
• Use alternate dewatering methods                                                                                                                                                    |
| Concentrated HTL aqueous product is not converted to bio-oil when recycled           | Low         | Low             | • Use alternate methods for treatment of HTL aqueous product (anaerobic digestion, or catalytic hydrothermal gasification)                                                                                                                       |
| Sewer conveyance of flue gas causes too much loss/dilution                          | Medium      | Low             | • Use a dedicated pipeline for transport of CO\textsubscript{2} from flue gas                                                                                                                      |
Summary of Major Project Activities

• Task 1- Project Management (Ongoing)
  • Monthly Progress Conference Calls with DOE Program Manager
  • Three Quarterly Progress Reports Submitted
  • Individual Meetings with Three Industrial Advisory Board Members

• Task 2- Algae Cultivation using Simulated Flue Gas w/Contaminants (Completed)
  • Demonstrated acclimation & robust growth of 2 algal species w/ acid gasses (CO₂, NOₓ, SO₂ₓ)
  • Demonstrated acclimation & robust growth of 2 algal species w/ heavy metals (As, Se, Hg, Cr, Cu)

• Task 3- Algae Cultivation w/ Wastewater Nutrients (Ongoing)
  • Demonstrated acclimation & robust growth of 2 algal species with 2 wastewater sidestreams
    • Centrate from wastewater biosolids centrifuge dewatering
    • Raw hydrothermal liquefaction (HTL) aqueous product from conversion of biomass to biofuels
  • >50% nutrient replacement achieved with all combinations of wastewater nutrients & algal species
  • Full nutrient replacement achieved with several combinations of wastewaters & algal species
  • Ongoing testing to optimize productivity of algal cultures
New Flue Gas Testing Capability
Small-Scale Algae Cultivation w/ Bottled Flue Gas Samples

<table>
<thead>
<tr>
<th></th>
<th>LOW FLUE GAS</th>
<th>MEDIUM FLUE GAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flue Gas CO₂ concentration</td>
<td>6.01%</td>
<td>6.01%</td>
</tr>
<tr>
<td>Air pumping rate (L/min)</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Flue gas Injection rate (L/min)</td>
<td>0.05</td>
<td>0.1</td>
</tr>
<tr>
<td>Influent CO₂ conc.</td>
<td>0.58%</td>
<td>1.04%</td>
</tr>
<tr>
<td>Exhaust CO₂ conc.</td>
<td>0.44%</td>
<td>0.85%</td>
</tr>
<tr>
<td>CO₂ removal efficiency</td>
<td>24%</td>
<td>18%</td>
</tr>
<tr>
<td>Carbon Capture (mg-C)</td>
<td>183.0</td>
<td>258.3</td>
</tr>
<tr>
<td>Assimilated Carbon (mg-C)</td>
<td>178.6</td>
<td>243.7</td>
</tr>
</tbody>
</table>