Microalgae Commodities from Coal Plant Flue Gas CO2
DE-FE0026490, 10/01/15–09/30/17, Andy Aurelio, Program Manager

John Benemann, P.I., Tryg Lundquist, Co-P.I., Kyle Poole, Project Engineer

MicroBio Engineering Inc.
PROJECT PARTICIPANTS

- MicroBio Engineering Inc. (MBE), Prime, P.I.: John Benemann, CEO
  TEAs, LCAs, gap analyses, ponds for OUC & UF, Project management
- Subrecipients:
  - Orlando Utilities Commission (OUC): Stanton Energy Center (SEC)
    power plant/site data; operate algae ponds at SEC with flue gas CO₂
  - Univ. of Florida (UF): operate test ponds, algae anaerobic digestion
  - Arizona State Univ.: Train OUC and UF staff in algae cultivation
  - Scripps Institution of Oceanography (SIO), Lifecycle Associates (LCA), SFA Pacific Inc.: LCA, TEA and engineering assistance to MBE

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• Algae Equipment
• R&D, Engineering Consulting
• Techno-Economic Analyses
• Life Cycle Assessments

• Wastewater Reclamation
• Biofuels, Biofertilizers
• AquaFeeds, Nutritionals
MicroBio Engineering Inc. RNEW® Process: Algal Wastewater Treatment with Biofuels Production, Water/Nutrients Reclamation, Biofertilizers

Recycle
Nutrients
Energy
Water
Algae cultures, wastewater treatment require CO$_2$

CO$_2$ supply maximizes algal biomass production and achieves complete nutrient assimilation in wastewater treatment.
Microalgae Municipal Wastewater treatment, Delhi, CA
Site of DOE BETO Funded Projects - MicroBio Engineering / CalPoly

Facultative Ponds (inflow)

Settling Ponds

Effluent Pond

Percolation/drying beds

Paddle wheels

Two 3.5-acre raceways
Two 3.5-acre raceways

Technology Background:
Municipal Wastewater treatment

Delhi, CA, Site of DOE BETO Supported Projects by MBE / CalPoly

Facultative Ponds (inflow)
Settling
Effluent Ponds
Pond Percolation/
drying beds
Algae harvested by in-pond settling, then solar dried

~100,000 gallons of ~3% solids algae biomass in settling basin

Concrete drying pad

Solar Dried Algae (for biofertilizer)
Low-Cost Conversion of Algal Biomass to Biogas (CH4/CO2) based on covered lagoon anaerobic digester technology (here 5 acre dairy wastewater digester in California)
DOE-NETL DE-FE0026490: Overall Project Objectives “Microalgae Commodities from Coal Plant Flue Gas CO2”

• Primary Objective: detailed site-specific Techno-economic Analysis (TEA) and Life Cycle Assessment (LCAs) for the Orlando Utilities Commission Stanton Energy Center (OUC-SEC) coal-fired power plant for CO₂ utilization /mitigation options.
Orlando Utilities Commission Stanton Energy Center (OUC-SEC) two ~450 MW Coal-fired Power Plants
Primary Objective: detailed site specific Techno-economic Analysis (TEA) and Life Cycle Assessment (LCAs) for the Orlando Utilities Commission Stanton energy Center (OUC-SEC) coal-fired power plant for CO₂ utilization /mitigation options:

**Case 1 (Budget Period 1)** Biogas production from algal biomass to replace coal for maximum CO₂ utilization and mitigation, and

**Case 2 (Budget Period 2)** Production of commodity microalgae animal feeds, for maximum beneficial economic use of flue gas CO₂
Case 1 (1st Yr): Flue-gas CO2 → Algae → biogas → power plant

Future Algae Farm
(100 ponds; 1,000 acres)

OUC-SEC
~900 MW Coal-fired PP
Case 1b. (1st Yr) Flue gas CO2 $\rightarrow$ Algae $\rightarrow$ biogas $\rightarrow$ RNG

- OUC-SEC ~900 MW Coal-fired PP
- Landfill
- Landfill Gas
- Flue Gas CO$_2$ & Electricity
- Future Algae Farm (100 ponds, 1,000 acres)
- Wastewater
- Biogas
- Renewable Natural Gas (RNG) to pipeline or Vehicle Fuel
Case 2. Algae $\rightarrow$ animal feed production (2\textsuperscript{nd} year, current)
DOE-NETL DE-FE0026490: Overall Project Objectives “Microalgae Commodities from Coal Plant Flue Gas CO2”

• **Primary Objective:** detailed site specific Techno-economic Analysis (TEA) and Life Cycle Assessment (LCAs) for the Orlando Utilities Commission Stanton energy Center OUC-SEC Coal-fired power plant for CO$_2$ utilization /mitigation options:

  * **Case 1 (Budget Period 1)** Biogas production from algal biomass to replace coal for maximum CO$_2$ mitigation (Budget Period 1), and

  * **Case 2 (Budget Period 2)** Production of commodity microalgae animal feeds, for maximum beneficial economic use of flue gas CO$_2$

• **Secondary Objective:** experimental work at OUC-SEC and UF to demonstrate biomass production using flue gas CO2 and native algal strains for conversion to biogas and animal feed
Experimental Work
Experimental work: growth of native algae in raceway ponds at OUC (with flue gas) and U. Florida (for biogas)

- Four 3.5-m² raceways at each location
- At OUC and UF, determine seasonal productivities of natural algal strains/consortia, optimize hydraulic residence times, analyze biochemical composition, effects of flue gas contaminants.
- At OUC, compare flue gas to pure CO₂.
- At UF, algal cultivation, biogas (methane) yields.
Experimental Algae Raceway™ Ponds fabricated by MicroBio Engineering Inc. (MBE) and installed /operated at/by OUC-SEC.
Flue gas from scrubbers to condensate traps to pump to pilot ponds
Flue gas from scrubbers to condensate traps to pump to pilot ponds with CO2 consumed by algae
Microalgae observed at OUC-SEC Ponds
Filamentous algae dominated the OUC Ponds, which allows for easy harvesting of the biomass.
Jan-Jun 2017 productivity averaged 14 g/m²-d at OUC. Weeks of rain are the major detriment to productivity.
Pilot ponds at University of Florida - Gainesville
At UF: Bioflocculating cultures that settle
SEC and UF algae anaerobically digested at UF to determine CH$_4$ yield
Site Selection for TEA/LCA at OUC-SEC for a commercial 1,000 acre system
Potential Sites near OUC-SEC

Site Selected for Study

OUC-SEC

~900 MW Coal-fired PP
Location of 1,000 acre (400 ha) algae farm 2 miles from OUC-SEC (flue gas transport is a major limitation)
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating Temperature/ Pressure</td>
<td>70 F / 40 psig</td>
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<tr>
<td>Flue Gas Composition</td>
<td>11% CO₂, balance N₂, some O₂ (trace contaminants, NOₓ, etc.)</td>
</tr>
<tr>
<td>Avg. Flow (15 g/m²-day biomass)</td>
<td>17,000 cfm @ 68 F and 1 atm/day</td>
</tr>
<tr>
<td>Peak hourly Flow (summer)</td>
<td>122,000 cfm @ 68 F and 1 atm/hr</td>
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</tbody>
</table>
Case 1 TEA/LCA.

Power Plant Flue Gas CO2 → Algae → Biogas

1a. Flue Gas CO2 → Algal Biomass → Biogas → Replace Coal

1b. Flue Gas CO2 → Algal Biomass → Biogas → RNG
Case 1a

Flue Gas CO2 $\rightarrow$ Algae Ponds $\rightarrow$ Biogas $\rightarrow$ Replace Coal

Farm Size: 400 ha (1,000 acres), 2 miles to OUC SEC Power Plant

Productivity*: 33 g afdw/m$^2$-day (annual average)*

50 g afdw/m$^2$-day (peak daily, in summer)*

Flue Gas CO2 Efficiency of Capture into Algal Biomass: 55%

Make-up Water Source: Municipal Wastewater Treatment Plant

Make-up Water Rate: 38,700 m$^3$/d (10 MGD)

*High productivity to be achieved by complete recycling of biogas digester effluents
Case 1a – Algae derived biogas to replace coal in PP.
### Case 1a. Biogas to Power Plant Carbon Utilization Summary

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal Electricity Carbon Intensity</td>
<td>286.5</td>
<td>g CO(_2)eq/MJe</td>
</tr>
<tr>
<td>Total Biogas HHV Energy Generated</td>
<td>492,138,000</td>
<td>MJ/yr</td>
</tr>
<tr>
<td>Total Biogas Electricity Generated</td>
<td>99,122,000</td>
<td>MJe/yr</td>
</tr>
<tr>
<td>Total Reduction in GHG Emissions</td>
<td>28,400</td>
<td>CO(_2)eq mt/yr</td>
</tr>
<tr>
<td>Percent of OUC-SEC Emissions</td>
<td>0.7%</td>
<td></td>
</tr>
</tbody>
</table>
Case 1a - Biogas to Power Plant: CAPEX Summary

Total Investment: $132, million

Debt: Equity financing 80:20%

Debt (Bond Payment, 20 yr @5%): $8,500,000 /yr

ROI (15%): $3,900,000 /yr

Case 1a - Biogas to Power Plant: OPEX Summary

CAPEX (Bond + Equity) $12,400,000 /yr

Operating Costs: $11,600,000 /yr

Biogas @ $2 /mmBtu: $933,000 /yr

CO₂ Mitigation Cost (biogas to replace coal): $816 /mt CO₂
Case 1b: Production of Renewable Natural Gas (RNG)

Flue Gas CO₂

Recirculation

Make-up Water & Nutrients

Algae Raceways

Gravity Harvesting

Filters

Power Station

Cooling Water

1% Solids

Media Recycle

Gravity Thickening

3% Solids

Digestate Nutrient Recycling

CO₂ Recycle

Digester

Biogas Upgrading

Renewable Natural Gas

Biofertilizer Option
Case 1b. Alternative Process: Algae WWT → biogas → RNG

Future Algae Farm (100 ponds; 1,000 acres)

Wastewater

Landfill Gas

Flue Gas CO₂ & Electricity

Biogas

Renewable Natural Gas (RNG) to pipeline or Vehicle Fuel

Landfill

OUC-SEC

~900 MW Coal-fired PP
Case 1b - RNG Alternative: Biogas production + Wastewater Treatment (*12 million gallons/day*); remove CO2 from biogas to upgrade to RNG (‘Renewable Natural Gas’) for pipelines, vehicles.

\[
\text{Wastewater Credit } \quad (\$1,750/\text{MG})
\]

\[
\text{RIN/LCFS Credits } \quad ($17/\text{mmBtu})^* 
\]

Costs = $816 / mt CO2
Revenues = $461 / mt CO2

NET : $355 /mt CO2 avoided
Case 1b - RNG Alternative: Biogas production + Wastewater Treatment (increase to 30 million gallons/day); remove CO2 from biogas to upgrade to RNG (‘Renewable Natural Gas’) for pipelines, vehicles.

Costs $816/mt CO2
Revenues: $806/mt CO2
Net: $10 /mt of CO2 emissions avoided
Case 2. Animal Feed Case
Animal Feed Case Design Parameters

Farm Size: 400 ha

Productivity: 18 g/m²*d (annual avg.) 35 g/m²–day (peak)

Flue Gas Source: OUC-SEC CFPP

Distance to Farm: 2 miles

Flue Gas CO₂ Uptake Efficiency: 55%

Water Source: Municipal Wastewater Treatment Plant

Blowdown Rate: 5%

Make-up Water Rate: 38,700 m³/d (10 MGD)
LCA Modeling Parameters

LCA Model Type: Long-term Consequential (Co-product allocation)

LCIA Method: US EPA TRACI v2.1

Modeling Software: openLCA

Data Sources:
• OUC-SEC specific flue gas characteristics
• Orange County reclaimed water characteristics
• Mass balance of algae, MBE ESPE model
• Ecoinvent US regional utilities (electricity, natural gas)
Soybean and Algae Feed Characteristics

<table>
<thead>
<tr>
<th></th>
<th>Soybeans*</th>
<th>Freshwater Algae*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protein</td>
<td>42%</td>
<td>45%</td>
</tr>
<tr>
<td>Oil</td>
<td>22%</td>
<td>20%</td>
</tr>
<tr>
<td>Carbohydrates &amp; Other Organics</td>
<td>36%</td>
<td>35%</td>
</tr>
<tr>
<td>Nitrogen Content</td>
<td>6.7%</td>
<td>7.2%</td>
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</tbody>
</table>

*Ash free dry weight basis, based on Soybeans 13% moisture and 4% ash content.
# Feed Content Essential Amino Acids

<table>
<thead>
<tr>
<th></th>
<th>Soybeans&lt;sup&gt;1&lt;/sup&gt;</th>
<th>Freshwater Algae&lt;sup&gt;2&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isoleucine</td>
<td>4.54</td>
<td>4.54</td>
</tr>
<tr>
<td>Leucine</td>
<td>7.78</td>
<td>8.56</td>
</tr>
<tr>
<td>Lysine</td>
<td>6.38</td>
<td>6.97</td>
</tr>
<tr>
<td>Methionine + Cystine</td>
<td>2.59</td>
<td>2.73</td>
</tr>
<tr>
<td>Phenylalanine + Tyrosine</td>
<td>8.08</td>
<td>8.63</td>
</tr>
<tr>
<td>Threonine</td>
<td>3.86</td>
<td>4.96</td>
</tr>
<tr>
<td>Valine</td>
<td>4.80</td>
<td>5.82</td>
</tr>
</tbody>
</table>


Filamentous Microalgae Animal Feed Production

- **Make-up Water & Nutrients**
- **Algae Raceways**
  - Flue Gas CO₂
  - Recirculation
  - Media Recycle
  - 5-10% Solids
- **Inline Canal Screens**
- **Screw Presses**
  - 20% Solids
- **Filters**
- **Power Station**
  - Cooling Water
  - Waste Heat Option
- **Rotary Drum Dryer**
  - 90% Solids
- **Animal Feed**
Animal Feed Financial Summary CAPEX

Total Capital Investment: $125,000,000
Percent financed by debt: 80%
Percent Financed by equity: 20%
Bond Payment (20 yr pond at 5%): = $8,030,000 /yr
Return on Equity (15%) = $3,750,000 /yr
Animal Feed Financial Summary OPEX

- Bond Repayment: $8,500,000 /yr
- Return on Equity: $3,900,000 /yr
- Operating Costs: $11,600,000 /yr
- Animal Feed Selling Price: $965/mt

LCA (Life Cycle Assessment) for Animal Feeds

**LCA Model Type:** Long-term Consequential (Co-products)

**LCIA Method:** US EPA TRACI v2.1

**Modeling Software:** openLCA

**Data Inputs:**
- OUC-SEC flue gas composition
- WWT Plant reclaimed water
- MicroBio Engineering Inc. TEA Algae TEA/Engineering Model
- Ecoinvent US regional utilities (electricity, natural gas)
Microalgae feed much lower GHG emissions than soybeans
Microalgae feed much lower GHG emissions than soybeans
# Animal Feed Carbon Utilization Summary

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<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>Global Warming Potential of Algae Feed</td>
<td>-0.473</td>
<td>kg CO2-eq/kg</td>
</tr>
<tr>
<td>Fraction of Carbon in Algal Biomass</td>
<td>47%</td>
<td></td>
</tr>
<tr>
<td>Mass of Algal Feed Produced</td>
<td>26,300</td>
<td>mt/yr</td>
</tr>
<tr>
<td>CO2 Captured in Feed</td>
<td>45,300</td>
<td>mt/yr</td>
</tr>
<tr>
<td>OUC-SEC CO2 Annual Emissions</td>
<td>4,200,000</td>
<td>mt/yr</td>
</tr>
<tr>
<td>Percent of CO2 Utilized</td>
<td>1.1%</td>
<td></td>
</tr>
</tbody>
</table>
Conclusions

• 400 ha (1000 acres) of algae production required for economics of scale. Utilizes ~1% of a 900 MW CFPP

• **Case 1. Biogas production.**
  – Wastewater treatment revenue is necessary to make carbon utilization economically feasible
  – Economics also depend on carbon markets (LCFS and RIN credits)

• **Case 2. Animal Feeds**
  – Algae feed similar nutritionally to soybean (protein, energy)
  – LCA for GHG highly favorable for microalgae feeds vs. soybeans
  – Project algae feed selling price: $965/mt, (~3 X soybeans)
Future Developments in Microalgae CO2 Utilization

- Technological advances required to achieve projected low CAPEX/OPEX
- Select/improve algal strains for productivity, stability, composition, etc.
- Develop Wastewater/Flue gas CO2 Utilization/Biogas to RNG Process
- Valorize algal nutritional components for higher value animal feeds.
- Commercialization in niche markets (biofertilizers, specialty feeds, etc.)

PROPOSED NEXT OUC-MBE PROJECT PHASE:
Expand ponds at OUC-SEC to four x 43 m²
Scale-up of filamentous algae at OUC-SEC
Flue gas CO2 utilization for algal feeds, fuels
Thanks to all participants in this project at MicroBio Engineering Inc., the Orlando Utilities Commission, U. of Florida, Arizona State Univ., Scripps Institution of Oceanography, Lifecycle Associates and SFA Pacific Inc. And DOE-FE - NETL and OUC for financial support.