A Combined Biological and Chemical Flue Gas Utilization System towards Carbon Dioxide Capture from Coal-fired Power Plants

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DOE Project Kick-off Meeting

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Outline

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- Scientific and Technical Merit
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  - Task 3. Developing a cascade biomass conversion process
  - Task 4. Conducting TEA and LCA on the studied process
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- Project Budget
Dr. Yan (Susie) Liu
Biosystems and Agricultural Engineering, Michigan State University
Responsible for algal cultivation

Dr. Mitch Smith
Chemistry, Michigan State University
Responsible for catalysis of polymer synthesis

Dr. Angela Wilson
Chemistry, Michigan State University
Responsible for formulation of amino acid based absorbents

Dr. Wei Liao
Biosystems and Agricultural Engineering, Michigan State University
Responsible for system integration, TEA and LCA

Mr. Bill Clary, Mr. Dave Pavlik, and Mr. Bob Morgan
PHYCO$_2$ LLC
Responsible for the reactor modification and pilot operation

Mr. Bob Ellerhorst and Mr. Nate Verhanovitz
The T.B. Simon Power Plant
Responsible for the connection between the pilot unit and the power plant operation
The goal:
The goal of the proposed project is to develop a combined biological and chemical system for coal-fired power plants to generate bio-based CO₂ absorbent and other value-added products.

Project objectives:
1. Optimizing the growth of the selected algal strain to maximize biomass accumulation from the coal-fired flue gas
2. Developing a cascade biomass utilization to produce amino acid absorbents, polyurethanes, biodiesel, and methane
3. Conducting techno-economic analysis (TEA) and life cycle assessment (LCA) of the proposed process

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The proposed biological and chemical algal cultivation system*
*: Solid black lines are the mass flow. Dashed blue lines are the energy flow. The red frame is the system that will be studied by this project.
Relevance and Outcomes

Carbon capture and utilization (CCU) vs. carbon capture and storage (CCS)

- Advantages of CCU over CCS
  - Economic advantage: CO₂ captured is used for chemical production and other value-added applications.
  - Technical advantage: CCU technologies can be tailored for different CO₂ release scenarios, and overcomes the limitations of geological storage requirements of CCS.

- Challenges of CCU technologies
  - Early stage development
  - Difficulty of current CCU technologies to utilize a sufficient amount of CO₂
  - Relatively cheap energy and material products
  - High value but low market volume products
Relevance and Outcomes

Algal based CCU technologies

- Advantages:
  - Photosynthesis using solar energy and minimum demand on nutrients (N and P)
  - Higher photosynthetic efficiency than most of land plants
  - Less impact of impurities (NOx and SO\textsubscript{2}) in the flue gas on CO\textsubscript{2} capture
  - Algal components (protein, carbohydrate, and lipid) for long-term carbon storage and utilization

- Challenges:
  - Carbon capture rate not matching with CO\textsubscript{2} emission rate from coal-fired power plant
  - A large amount of water required to support algal cultivation
  - Extremely large footprint of algal facility to capture CO\textsubscript{2} in the flue gas from coal-fired power plant
  - Full utilization of algal components for value-added chemical production

Comparison of photosynthetic efficiency

<table>
<thead>
<tr>
<th>Crop</th>
<th>Biomass productivity (metric ton/ha/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat (fruit + straw)</td>
<td>11</td>
</tr>
<tr>
<td>Miscanthus</td>
<td>16</td>
</tr>
<tr>
<td>Switchgrass</td>
<td>10</td>
</tr>
<tr>
<td>Microalgae (Optimized)</td>
<td>60</td>
</tr>
<tr>
<td>Microalgae (Theoretical)</td>
<td>120</td>
</tr>
</tbody>
</table>

A culture system with a reactor volume of 5,000,000 m\textsuperscript{3} is needed to completely capture CO\textsubscript{2} from a 160 MW power plant

Large footprint of algal cultivation

From: http://www.cyanotech.com/company/facility.html
Relevance and Outcomes

**Expected outcomes of the project**

- Long-term culture stability of the selected algal strains will be achieved using flue gas as the carbon source.
- Algal biomass productivity reaches 0.5-0.8 g/L/day at a biomass concentration of 1.2 g/L from the pilot operation.
- The cascade utilization process will achieve nearly 100% utilization of the algal biomass for amino acid salt absorbent, polymer, biodiesel, and methane production.
- The combined biological and chemical flue gas utilization will lead to a technically sound and economically feasible system that is able to efficiently capture CO$_2$ in the coal-fired flue gas.

The pilot photobioreactor system in the T.B. Simon power plant

a. T.B. Simon power plant; b. Flue gas pumping unit; c. Photobioreactor; d. Algae growing in the reactor; e. Centrifuge; f. Dryer
**Scientific and Technical Merit**

**Previous studies and supportive data**

1. A robust algal strain from Great lake region

   - A robust green alga, *Chlorella*, has been selected from Great Lake region to capture algal biomass and produce algal biomass.

   ![Pie charts showing algal assemblage changes](chart.png)

   **Changes of the algal assemblage during 5 months continuous culture**

   - *Pseudanabaena*
   - *Phormidium*
   - *Limnothrix*
   - *Synechocystis*
   - *Scenedesmus*

   ![Flask culture (250 ml)](flask.png)

   Algal community assemblages before (a) and after (b) cultured in AD effluent for 5 months

   ![Effects of different wavelengths on algae](effects.png)
Scientific and Technical Merit

Previous studies and supportive data

2. Characteristics of algal biomass

- The *Chlorella* biomass is rich in proteins, carbohydrates, and lipids.
- Eighteen major amino acids have been identified from the hydrolysis of the algal protein.

### Characteristics of algal biomass

<table>
<thead>
<tr>
<th>Properties</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crude proteins (% dry biomass)</td>
<td>47.3 ± 0.9</td>
</tr>
<tr>
<td>Lipids (% dry biomass)</td>
<td>10.6 ± 1.8</td>
</tr>
<tr>
<td>Carbohydrates (% dry biomass)</td>
<td>36.6 ± 0.8</td>
</tr>
<tr>
<td>Ash (% dry biomass)</td>
<td>8.4 ± 1.0</td>
</tr>
</tbody>
</table>

### Amino acid profile of the algal biomass

<table>
<thead>
<tr>
<th>Amino acids</th>
<th>g per 100 g proteins</th>
<th>Amino acids</th>
<th>g per 100 g proteins</th>
</tr>
</thead>
<tbody>
<tr>
<td>Histidine</td>
<td>1.7</td>
<td>Valine</td>
<td>5.9</td>
</tr>
<tr>
<td>Isoleucine</td>
<td>3.9</td>
<td>Arginine</td>
<td>7.2</td>
</tr>
<tr>
<td>Leucine</td>
<td>8.3</td>
<td>Cysteine</td>
<td>1.3</td>
</tr>
<tr>
<td>Lysine</td>
<td>5.8</td>
<td>Glycine</td>
<td>5.7</td>
</tr>
<tr>
<td>Methionine</td>
<td>2.1</td>
<td>Proline</td>
<td>4.4</td>
</tr>
<tr>
<td>Phenylalanine</td>
<td>5.1</td>
<td>Tyrosine</td>
<td>3.5</td>
</tr>
<tr>
<td>Threonine</td>
<td>50</td>
<td>Alanine</td>
<td>8.3</td>
</tr>
<tr>
<td>Tryptophan</td>
<td>0.7</td>
<td>Aspartic Acid</td>
<td>8.8</td>
</tr>
<tr>
<td>Serine</td>
<td>4.0</td>
<td>Glutamic Acid</td>
<td>11.2</td>
</tr>
</tbody>
</table>

Culture in bench-scale race-way reactors (20 L)

Culture in the outdoor race-way pond (0.5 acre)
Scientific and Technical Merit

Previous studies and supportive data

2. Characteristics of algal biomass

- The algal lipid can be used to produce high-quality biodiesel.
- The algal protein can be converted into polyurethane.
- The algal carbohydrates and other components can be used to generate fuel methane.

Algal biodiesel quality

<table>
<thead>
<tr>
<th>Properties</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>FAME composition</td>
<td></td>
</tr>
<tr>
<td>SFA (%)</td>
<td>37.27</td>
</tr>
<tr>
<td>MUFA (%)</td>
<td>31.59</td>
</tr>
<tr>
<td>PUFA (%)</td>
<td>31.14</td>
</tr>
<tr>
<td>Fuel properties</td>
<td></td>
</tr>
<tr>
<td>CN</td>
<td>50.83</td>
</tr>
<tr>
<td>SV (mg KOH/g biodiesel)</td>
<td>206.95</td>
</tr>
<tr>
<td>IV (g I/100 g biodiesel)</td>
<td>97.06</td>
</tr>
<tr>
<td>DU</td>
<td>93.86</td>
</tr>
<tr>
<td>LCSF</td>
<td>4.17</td>
</tr>
<tr>
<td>CFPP (°C)</td>
<td>-3.38</td>
</tr>
</tbody>
</table>

Methane production of anaerobic digestion of algal biomass residues

<table>
<thead>
<tr>
<th>Algal biomass residues loading ratio (%)</th>
<th>Animal manure loading ratio (%)</th>
<th>Specific methane yield (L CH₄/g VS/d)</th>
<th>Volumetric productivity (L CH₄/L/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>50</td>
<td>0.54</td>
<td>1.62</td>
</tr>
<tr>
<td>0</td>
<td>100</td>
<td>0.41</td>
<td>1.10</td>
</tr>
</tbody>
</table>

Characteristics of polyurethane foam from algal protein

<table>
<thead>
<tr>
<th>Polyurethane foam</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Core density (kg/m³)</td>
<td>40</td>
</tr>
<tr>
<td>Compressive strength (kPa)</td>
<td>165</td>
</tr>
<tr>
<td>Resiliency (%)</td>
<td>55</td>
</tr>
<tr>
<td>Elongation (%)</td>
<td>50</td>
</tr>
</tbody>
</table>

*: S-, MU-, and PU-FA represent saturated, mono-unsaturated and poly-unsaturated fatty acids, respectively; CN represents cetane number; IV represents iodine value; SV represents saponification value; SV represents cold filter plugging point; and DU represents degree of unsaturation.
Previous studies and supportive data

3. Amino acid salt solution as an absorption agent

- Aqueous amine solutions are the agent that is commercially available for post-combustion CO\(_2\) capture.
- Amino acid salt solution as the absorption agent overcomes the drawbacks of aqueous amine solutions: toxic chemicals and thermal degradation.
- Amino acids have a unique structure of possessing both an carboxylic acid and an amine, which is able to yield dipolar ions.
  - Low vapor pressures
  - Fast reaction kinetics
  - High absorption cycling
  - Good stability toward oxygen

Absorption and stripping process of using amino acid salt*

Chemical reactions of amino acid salt CO\(_2\) absorption*

- **Amine formation**: \(\text{OOC-R-NH}_3^+ + \text{KOH} \rightarrow \text{K}^+ + \text{OOC-R-NH}_2 + \text{H}_2\text{O}\)
  
  **Carbamate formation**: \(\text{CO}_2 + 2'\text{OOC-R-NH}_2 \leftrightarrow \text{OOC-R-NH-COO}^- + \text{OOC-R-NH}_3^+\)

- **Carbamate hydrolysis**: \(\text{OOC-R-NH-COO}^- + \text{H}_2\text{O} \leftrightarrow \text{OOC-R-NH}_2 + \text{HCO}_3^-\)
  
  **Bicarbonate formation**: \(\text{CO}_2 + \text{OOC-R-NH}_2 + \text{H}_2\text{O} \leftrightarrow \text{OOC-R-NH}_3^++ \text{HCO}_3^-\)

*: From: J.P. Brouwer, TNO Science & Industry, The Netherlands
Scientific and Technical Merit

Preliminary TEA analysis

Mass balance

- The preliminary mass balance analysis was based on the proposed system (not including the power plant operation) for a 160 MW coal-fired power plant.
- The power plant burns subbituminous coal and generates 1.2 million metric tons of CO₂, 6,000 metric tons of N₂O, and 3,000 metric tons of SO₂ per year.

\[
\text{CO}_2 \text{ from the coal-fired power plant} \\
\quad \text{The amount: 3,287,700 kg/day}
\]

\[
\text{CO}_2 \text{ for the algal cultivation} \\
\quad \text{The amount of CO}_2 \text{ pumped into the algal system: 76,510 kg/day}
\]

\[
\text{Water added} \\
\quad \text{Volume: 2.8 m}^3/\text{day}
\]

\[
\text{CO}_2 \text{ for the algal cultivation} \\
\quad \text{The amount of CO}_2 \text{ pumped into the algal system: 76,510 kg/day}
\]

\[
\text{Water recycled} \\
\quad \text{Volume: 697.2 m}^3/\text{day} \\
\quad \text{Nitrogen: 100 mg/L} \\
\quad \text{Phosphorous: 37.5 mg/L}
\]

\[
\text{High-rate photobioreactors} \\
\quad \text{Reactor volume: 1.749 m}^3/\text{day} \\
\quad \text{Retention time: 2.5 days}
\]

\[
\text{The remained CO}_2 \text{ after the algal culture:} \\
\quad \text{The amount: 75,356 kg/day}
\]

\[
\text{Water recycled} \\
\quad \text{Volume: 697.2 m}^3/\text{day} \\
\quad \text{Nitrogen: 100 mg/L} \\
\quad \text{Phosphorous: 37.5 mg/L}
\]

\[
\text{Harvesting and dewatering} \\
\quad \text{Harvesting volume: 700 m}^3/\text{day}
\]

\[
\text{Algae biomass} \\
\quad \text{Amount: 2,798 kg/day, wet basis} \\
\quad \text{Dry matter: 25%}
\]

\[
\text{Amino-acid salt CO}_2 \text{ capture} \\
\quad \text{CO}_2/\text{amino acid mole ratio: 0.4} \\
\quad \text{Amino acid salt conc.: 4 M} \\
\quad \text{Solvent amount: 357,799 kg} \\
\quad \text{Solvent flow rate: 16 m}^3/\text{tCO}_2 \\
\quad \text{Amino-acid consumed: 0.1 kg/CO}_2
\]

\[
\text{Amino acid in the spent absorbent} \\
\quad \text{Amount: 328.8 kg/day}
\]

\[
\text{Diesel} \\
\quad \text{Amount: 74.1 kg/day}
\]

\[
\text{Methane} \quad a \\
\quad \text{Amount: 98.7 kg/day}
\]

\[
\text{Polymer} \quad b \\
\quad \text{Amount: 1,096 kg/day}
\]

\[
\text{Pure CO}_2 \\
\quad \text{Amount: 3,286,546 kg/day}
\]

---

a. The calculation is based on 50:50 mixing of algal carbohydrate and dairy manure from the data in Section 3.5.7.
b. The calculation is based on that 30% (w/w) of polymer is from amino acid.
c. The amount of amino acid salt solution is 357 metric ton.
Scientific and Technical Merit

Preliminary TEA analysis

Energy balance

- The energy balance analysis was based on the previous mass balance.
- The 160 megawatts coal-fired power plant generates 14,416,457 GJ/year for both electricity and heat.

<table>
<thead>
<tr>
<th>System components</th>
<th>Energy value (GJ/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>The proposed system b</td>
</tr>
<tr>
<td><strong>Chemical production</strong></td>
<td></td>
</tr>
<tr>
<td>Energy input</td>
<td>-2,184</td>
</tr>
<tr>
<td>Energy output</td>
<td>2,920</td>
</tr>
<tr>
<td><strong>CO₂ capture</strong></td>
<td></td>
</tr>
<tr>
<td>Energy input</td>
<td>-2,759,055</td>
</tr>
<tr>
<td>Energy output</td>
<td>-</td>
</tr>
<tr>
<td>Total energy input</td>
<td>-2,761,389</td>
</tr>
<tr>
<td>Total energy output</td>
<td>1,920</td>
</tr>
<tr>
<td><strong>Net energy</strong></td>
<td>-2,759,469</td>
</tr>
</tbody>
</table>

a. Data used in the calculation are from the pilot scale algal cultivation and previous lab-scale utilization experiments. The energy input is assigned as negative. The energy out is assigned as positive.
b. The proposed system consists of algae photobioreactor cultivation, cascade biomass utilization, and CO₂ capture.
c. The single amino acid salt process includes both amino acid production and amino acid salt absorption.
d. The MEA process includes MEA production and MEA CO₂ capture.
Scientific and Technical Merit

Preliminary TEA analysis

Economic analysis

- According to the mass balance analysis, the proposed system can produce 400 metric tons of polyurethane, 35 metric tons of methane, and 27 metric tons of biodiesel besides approximately 200 metric tons of amino acid salt absorbent.
- The proposed system could lead to a positive economic impact on the power industry.

<table>
<thead>
<tr>
<th>System components \ System components</th>
<th>The proposed system</th>
<th>The amino acid salt process</th>
<th>MEA process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operational cost ($/year)</td>
<td>-400,000</td>
<td>-360,036</td>
<td>-120,000</td>
</tr>
<tr>
<td>Income ($/year)</td>
<td>849,018</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Revenue ($/year)</td>
<td>449,018</td>
<td>-360,036</td>
<td>-120,000</td>
</tr>
</tbody>
</table>

a. The cost is assigned as negative. The income is assigned as positive. The capital cost is not included in the analysis. It is assumed that the energy for CO₂ capture for all three processes are from residual energy. The cost of energy consumption is not included in the analysis.
b. The operation needs four operators ($60,000/operator/year). The cost of maintenance and other supplies is $160,000. With the current price of biodiesel ($1.25/kg), polyurethane ($2/kg), and methane ($0.42/kg), the annual income would be $849,018.
c. The amino acid cost (based on lysine) is $3/kg. The amount of amino acid required is 120,012 kg.
d. The MEA cost (Monoethanolamine) is $1/kg. The amount of MEA required to capture 1.2 million ton CO₂ is 120,000 kg.
Scientific and Technical Merit

Preliminary life cycle analysis of greenhouse gas emission

- The greenhouse gas emission is analyzed for **chemical production section (not including the power plant and CO₂ capture and utilization)**.

<table>
<thead>
<tr>
<th>Greenhouse gas release from the chemical production (metric ton CO₂-e per year)</th>
<th>The proposed system b</th>
<th>The amino acid salt process c</th>
<th>MEA process d</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-421</td>
<td>648</td>
<td>171.6</td>
</tr>
</tbody>
</table>

a. The positive numbers mean greenhouse gas release. The negative number means greenhouse gas reduction.
b. The algal culture uptakes 1,154 kg CO₂/day.
c. The CO₂-e for amino acid production is 5.4 kg CO₂-e per kg amino acid. The amount of amino acid required by the process is 120,012 kg/year.
d. The CO₂-e for MEA production is 171,600 kg per year based on the amount of fossil carbon used to manufacture MEA.
Scientific and Technical Merit

Product market potential

- **Biodiesel**
  - The amount of biodiesel produced in 2015 is 1,268 million gallons and expected to reach 1,705 million gallons in 2020.
  - Considering the total capacity of coal-fired and natural gas power plants in the U.S., the power industry can generate 47 million gallons of biodiesel.

- **Polymer**
  - The global polyurethane demand is approximately 15 million metric tons per year with a 5-6% annual increase in next 10-20 years.
  - Implementing the proposed system to the U.S. power industry could produce more than 2 million metric tons of biopolyols for the polymer industry.

- **Amino acid**
  - Current amino acid production is mainly for food and medical applications. The production scale and cost prohibit their application of CO$_2$ capture.
  - Algal biomass production on flue gas could address the issues of amino acid availability and cost for absorbent production.

### Global polyurethane market sectors

<table>
<thead>
<tr>
<th>Material</th>
<th>Production (metric ton/year)</th>
<th>Unit price ($/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexible foams</td>
<td>54%</td>
<td></td>
</tr>
<tr>
<td>Rigid foams</td>
<td>25%</td>
<td></td>
</tr>
<tr>
<td>Elastomers</td>
<td>15%</td>
<td></td>
</tr>
<tr>
<td>Adhesives</td>
<td>6%</td>
<td></td>
</tr>
</tbody>
</table>

### Global amino acid market

<table>
<thead>
<tr>
<th>Amino acid</th>
<th>Production (metric ton/year)</th>
<th>Unit price ($/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glutamic acid</td>
<td>1,000,000</td>
<td>5</td>
</tr>
<tr>
<td>Lysine</td>
<td>350,000</td>
<td>3</td>
</tr>
<tr>
<td>Methionine</td>
<td>250,000</td>
<td>3</td>
</tr>
</tbody>
</table>
Technical Approach

Task 1. Project management and planning (Dr. Liao)

- The project objectives are scheduled to be accomplished in accordance with the timeline and based on the management structure and responsibilities in the Project Management Plan.

- The project team will meet quarterly to evaluate progress, analyze problems encountered, and devise new plans to make sure the research efforts stay on the proposed timeline.

- The project director (PD) will communicate with the DOE project officer on a quarterly basis to discuss the progress.

- Brief quarterly progress reports will be developed and submitted.

- Annual reports will be developed to detail research outcomes on individual tasks, and discuss milestones and go/no-go decision points.
Technical Approach

Task 2. Optimizing the pilot-scale photobioreactor algae cultivation to maximize the biomass accumulation from the coal-fired flue gas (Dr. Liu, PHYCO2 LLC, Dr. Liao, and T. B. Simon Power Plant)

- This task will optimize and validate continuous algae cultivation using the pilot photobioreactors.

- Experimental plan
  - The algal strain: the selected *Chlorella sp.*
  - Culture system preparation: The SO$_2$ and NO$_2$ will be mixed with the flue gas from the T.B. Simon power plant to simulate the coal-fired flue gas. The equipment used for the pilot system are demonstrated in the following figure.
  - Operation of the algal cultivation: A CRD will be applied to assess the effects of flue gas flow rate and harvesting volume on algal biomass accumulation. Biomass will be accumulated for the following studies.

- Expected outcomes
  - Two-year continuous culture on coal-fired flue gas without major contamination will be achieved.
  - An optimized photobioreactor cultivation can generate more than 0.5 g/L/day dry algal biomass.

The pilot facility at the MSU power plant to capture CO$_2$ in flue gas

a. T.B. Simon power plant; b. Flue gas pumping unit; c. PHYCO2 facility in the power plant; d. The helix algal bioreactor; e. The bioreactor with cover and light; f. Centrifuge; g. Nutrient tanks; h. Nutrient pumping unit; i. Drying unit
Technical Approach

Task 3. Developing a cascade biomass conversion to produce amino acid absorbents, polyurethane, biodiesel, and methane (Drs. Liao, Smith, and Wilson)

- This task will mainly focus on developing high-efficiency protein extraction, optimizing mixed amino acid salt solution, and studying the one-pot liquefaction of biopolyol and polyurethane production.

- Expected outcomes
  - The amino acid salt solutions have a high CO$_2$ absorption capacity of more than 0.5 mole CO$_2$/mole amino acids,
  - The cascade process can utilize all algal components (except ash) to fuels and polymers.
Technical Approach

Task 3. Developing a cascade biomass conversion to produce amino acid absorbents, polyurethane, biodiesel, and methane (Drs. Liao, Smith, and Wilson)

- Sub-task 3.1. High-efficiency protein extraction and hydrolysis (Dr. Liao)
  - A multi-step process including alkaline homogenization and alkaline protease will be developed and optimized to maximize algal protein extraction.
  - Alkali hydrolysis (KOH) of the extracted protein for amino acid salt solution production

- Sub-task 3.2. Optimization of amino acid salt solution as an acidic gas absorbent (Drs. Wilson and Liao)
  - Molecular dynamic methods will be applied to delineate the impacts of animal acid on functionality of their salts, and conclude a preferred mixed amino acid solution as the absorbent for CO₂ absorption.

- Sub-task 3.3. One-pot synthesis of biopolyol for polyurethane production (Drs. Smith and Liao)
  - The amino acids will be mixed with ethylenediamine and then ethylene carbonate in a single reactor with different reaction conditions to produce hydroxyl-terminated polyols.
  - The resulted polyol will be blended with isocyannate by a high-torque mixer to produce polyurethane form.

Molecular dynamic simulation (a) before and (b) after formation of carbamate. From: Ma, C et al. 2014. J. Phys. Chem. Lett. 5. 1672-1677
Technical Approach

Task 4. Conducting TEA and LCA on the studied process (Drs. Liao and Liu and PHYCO2 LLC)

- **TEA**
  - Aspen Plus® and Matlab® will be used as the tool to carry out the TEA.
  - The system boundary will include both power plant and carbon utilization. The final products will be biodiesel, absorbent, polymers, and biomethane electricity.
  - The analysis will be based on a 160 MW coal-fired power plant (Erickson Power Plant in Lansing, MI)

- **LCA**
  - GREET and Excel will be used as the tools to carry out LCA using the same boundary for TEA.
  - Greenhouse gas emission and other environmental impact factors will be targeted as the outputs of the LCA.

Procedure of TEA and LCA
Task 5. Technology gap analysis (The entire project team)

- Technology gap analysis will provide a realistic view of the required research and development to fully commercialize the studied system.

- Experimental plan:
  - The data from the previous TEA will be used for the technology gap analysis.
  - A control operation (power plant with algal biofuel production) will be used as the baseline.
  - Sensitivity analysis will be used to identify the key technologies (unit operations) that limit the implementation of the proposed system.

- Expected outcomes:
  - A summary table of individual flowcharts will be concluded. The rows in the table will include individual components in the studied system. The columns in the table will be used to present current research status, technology readiness levels, potential vendors for the unit, R&D gap, and future R&D direction.
Management structure and responsibilities

- **Management structure**

  ![Diagram of management structure]

  - **The project Director**: The PD is in charge of authority and responsibility for managing research & development and pilot operations. Specific responsibilities of the director include:
    - Overseeing development of project tasks, scope and budget
    - Functioning as the point-of-contact for project matters to all parties internally and externally
    - Developing project performance measures, and monitoring and evaluating project performance throughout the life cycle of the project
    - Coordinating with PIs, power plant manager and operators, and other personals involved in the project
    - Participating in quarterly project reviews
    - Preparing progress reports to DOE

  - **PIs**: Each individual task of implementation, operation, and R&D is assigned to PI(s). The PIs will work with the PD to ensure the fulfillment of individual tasks. The specific PIs’ responsibilities are:
    - Providing day-to-day oversight of the tasks to ensure timely execution
    - Monitoring, reviewing, evaluating and reporting the performance of the project against established technical, cost, and schedule performance baselines
    - Maintaining project data in the project performance measurement and reporting system
    - Assisting the PD to prepare progress reports
## Risk management

- Potential risks and mitigation plans

<table>
<thead>
<tr>
<th>Risk type</th>
<th>Risk Level</th>
<th>Impact</th>
<th>Mitigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technical risks</td>
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<td></td>
</tr>
<tr>
<td>pH drop</td>
<td>Low</td>
<td>Slow algal growth and low biomass productivity</td>
<td>A pH feedback loop will be installed to control the CO\textsubscript{2} feeding rate.</td>
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<tr>
<td>Biofilm formation</td>
<td>Medium</td>
<td>Reduced photosynthesis efficiency</td>
<td>Rubber string balls will be added into the reactor to clean up the biofilm.</td>
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<tr>
<td>Process complexity of cascade conversion</td>
<td>High</td>
<td>Unfavorable mass and energy balance</td>
<td>Simplifying individual unit operations in the cascade conversion process could alleviate the negative impact of process complexity.</td>
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<tr>
<td>Management risk</td>
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<tr>
<td>Steady flue gas supply</td>
<td>Low</td>
<td>Flue gas shut down due to the maintenance</td>
<td>Gas cylinders will be used as a backup flue gas flow to support the algal culture system.</td>
</tr>
</tbody>
</table>
Detailed Project Management Plan

Project timeline and milestones

<table>
<thead>
<tr>
<th>Tasks</th>
<th>Start Date</th>
<th>End date</th>
<th>Cost</th>
<th>Budget period 1 (10/1/2017-9/30/2018)</th>
<th>Budget period 2 (10/1/2018-9/30/2019)</th>
<th>Budget period 3 (10/1/2019-9/30/2020)</th>
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<td>1 2 3 4</td>
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<td>9/30/2020</td>
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<td>1.2 – Briefings and reports</td>
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<tr>
<td><strong>Milestones</strong></td>
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</tr>
<tr>
<td>Kick-off meeting presentation</td>
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</tr>
<tr>
<td>Quarterly progress report</td>
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<tr>
<td>Annual report</td>
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<td>9/30/2019</td>
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<td><strong>Milestones</strong></td>
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<tr>
<td>pH is stable at 6.5 at the flue gas rate of 120 L/min</td>
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<tr>
<td>No bacterial contamination in 12 months operation</td>
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<tr>
<td>Algal biomass concentration reaches 1.2 g/L</td>
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<tr>
<td>Algal biomass productivity reaches 0.5 g/L/day</td>
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<td></td>
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<tr>
<td>The optimal culture conditions are concluded</td>
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<td>3.0 – Developing a cascade conversion process</td>
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<td>3.1 – High-efficiency protein extraction</td>
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<td>3.2 – Optimization of mixed amino acid solution</td>
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<td>3.3 – One-pot syntheses of biopolyl</td>
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<td>Amino acid yield reaches 90% of the algal protein</td>
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<td>Mixed amino acid salt solution has a absorption capacity of 0.5 mole CO₂/mole amino acid salt</td>
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<td>The spend amino acid solution can be converted to biopolyl at a conversion of 80%</td>
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<td>With biodiesel and methane production, cascade conversion can achieve 100% of algal biomass utilization (not counting ash)</td>
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<td>4.0 – Conducting TEA and LCA</td>
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<td>A detailed TEA on a full scale system based on a 160 megawatts coal-fired power plant will be delivered</td>
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<td>A detailed summary of R&amp;D gaps will be delivered</td>
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# Milestone log

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<th>Budget period</th>
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<th>Task number</th>
<th>Milestone description</th>
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<th>Actual completion date</th>
<th>Verification method</th>
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<td>The end of each quarter</td>
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<td>The end of each budget period</td>
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<td>Algal biomass productivity reaches 0.5 g/L/day</td>
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<td>3</td>
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<td>The spend amino acid solution can be converted to biopolyol at a conversion of 80%</td>
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<td>3</td>
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<td>With biodiesel and methane production, cascade conversion can achieve 100% of algal biomass utilization (not counting ash)</td>
<td>9/30/2020</td>
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<td>3</td>
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<td>A detailed TEA on a full scale system based on a 160 megawatts coal-fired power plant will be delivered</td>
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<tr>
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<td>A detailed LCA on a full scale system based on a 160 megawatts coal-fired power plant will be delivered</td>
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<td>Annual report</td>
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<td>9/30/2020</td>
<td></td>
<td>Annual report/Final report</td>
</tr>
</tbody>
</table>
# Detailed Project Management Plan

## Project go/no-go decision point

<table>
<thead>
<tr>
<th>Decision point (DP)</th>
<th>Date</th>
<th>Success criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>DP 1. Continuous culture of the photobioreactor</td>
<td>8/15/2018</td>
<td>Achieving the long-term stability of algal culture will be achieved (around 8-9 month continuous culture without any contamination issues)</td>
</tr>
</tbody>
</table>
| DP 2. Continuous project to conduct TEA and LCA          | 8/15/2019 | Realizing 100% of algal biomass utilization using the cascade conversion process  
                      - Developing an algae-based amino acid salt solution that has a CO₂ capture capacity of 0.5 mole CO₂/mole amino acid solution |
## Project Budget

<table>
<thead>
<tr>
<th>Budget period</th>
<th>Fiscal year</th>
<th>Performer</th>
<th>Federal cost ($)</th>
<th>Non-federal cost share ($)</th>
<th>Total cost ($)</th>
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<tbody>
<tr>
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<td>FY17</td>
<td>MSU</td>
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<td>999,976</td>
<td>269,014</td>
<td>1,268,990</td>
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</tbody>
</table>
The MSU Anaerobic Digestion Research and Education Center

Supportive Facilities

- Main building
- High-bay area
- Wet labs
- Solar panels
- Hot room
- Container-based self-sufficiency unit
- CSTR system (2000 m$^3$, 0.5 MW)
- Plug flow system (1000 m$^3$)
- Algal race-way system (1,600 m$^2$ pond)

Homepage: [http://www.egr.msu.edu/bae/adrec/](http://www.egr.msu.edu/bae/adrec/)
Thank you

Go Green !!