MICHIGAN STATE
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PHYCO₂

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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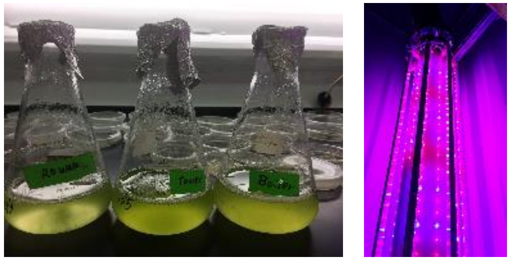
  - Task 5. Technology gas analysis
- Detailed Project Management Plan
- Project Budget

90 MW T.B. Simon Power Plant



Algal cultivation on flue gas and wastewater from the power plant

MSU race-way algal cultivation

Project Team

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

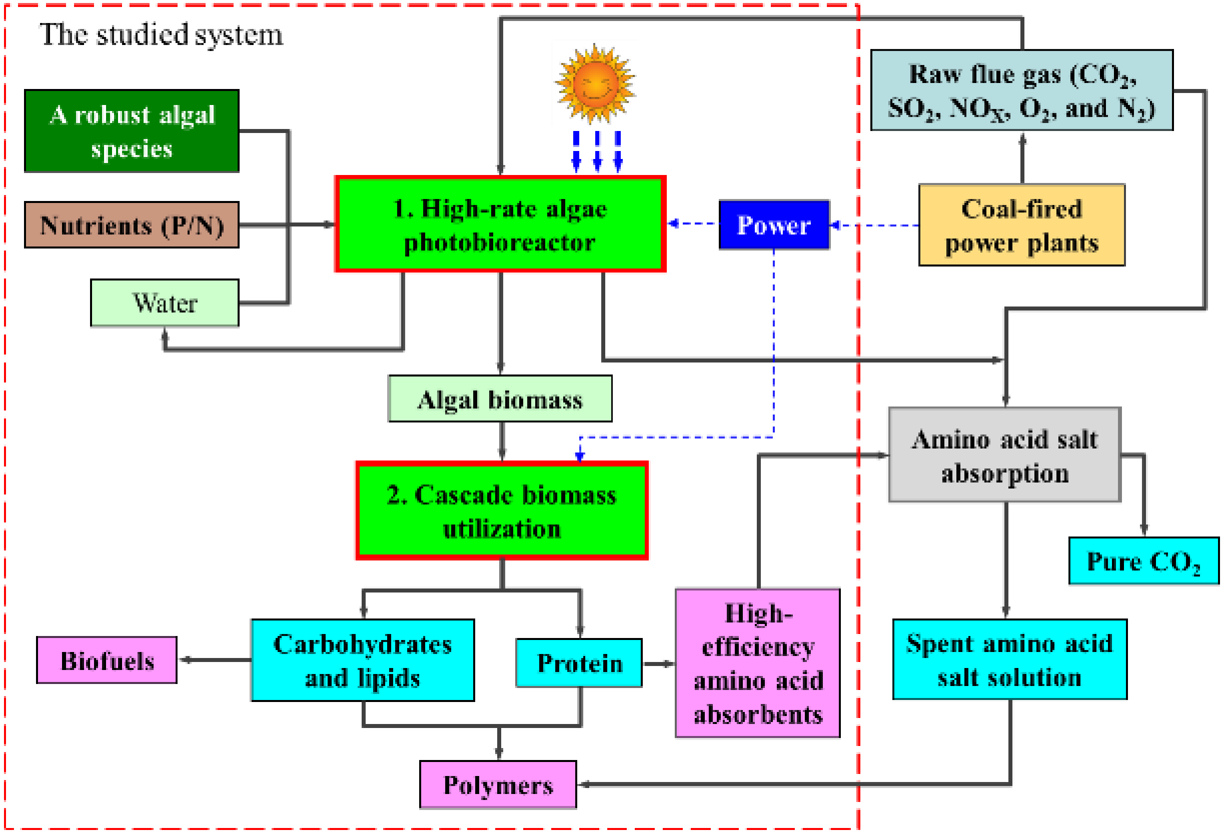
Project Objectives

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 CO_2 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



The proposed biological and chemical algal cultivation system*

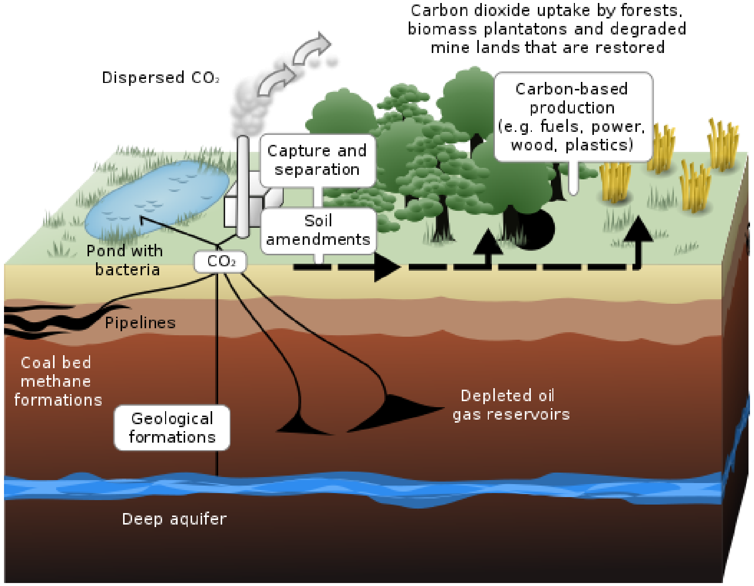
*: Solid black lines are the mass flow. Dashed blue lines are the energy flow. The red frame is the system that will be studied by this project.

Relevance and Outcomes

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

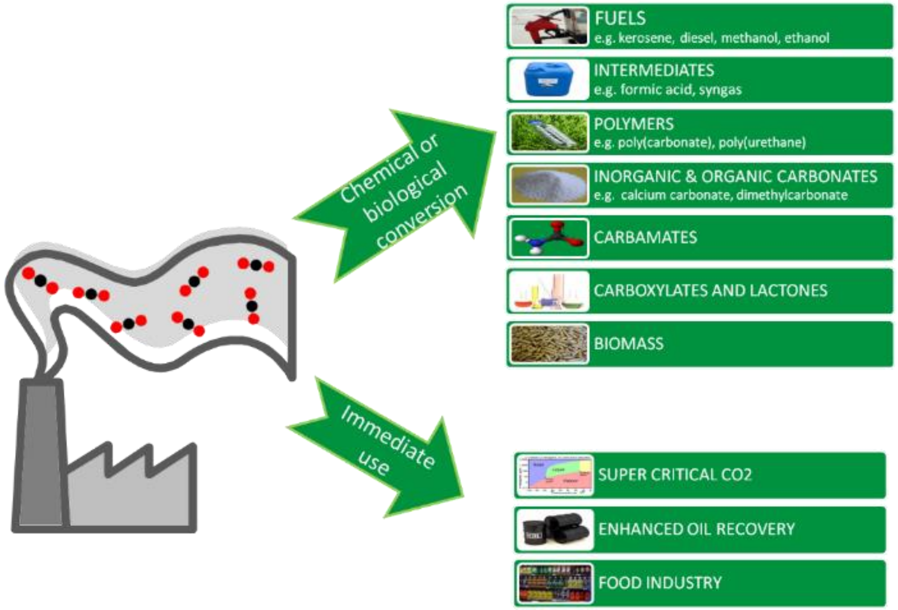
- Advantages of CCU over CCS
  - Economic advantage: CO_2 captured is used for chemical production and other value-added applications.
  - Technical advantage: CCU technologies can be tailored for different CO_2 release scenarios, and overcomes the limitations of geological storage requirements of CCS.

- Challenges of CCU technologies
  - Early stage development
  - Difficulty of current CCU technologies to utilize a sufficient amount of CO_2
  - Relatively cheap energy and material products
  - High value but low market volume products



Carbon capture and storage (CCS)

From: https://en.wikipedia.org/wiki/Carbon_capture_and_storage



Carbon capture and utilization (CCU)

From: http://co2chem.co.uk/wp-content/uploads/2013/07/Uses-dark-green.png

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_2) in the flue gas on CO_2 capture
  - Algal components (protein, carbohydrate, and lipid) for long-term carbon storage and utilization
- Challenges:
  - Carbon capture rate not matching with CO_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_2 in the flue gas from coal-fired power plant
  - Full utilization of algal components for value-added chemical production

Comparison of photosynthetic efficiency

Crop	**Biomass productivity (metric ton/ha/year)**
Wheat (fruit + straw)	11
Miscanthus	16
Switchgrass	10
Microalgae (Optimized)	**60**
Microalgae (Theoretical)	**120**

A culture system with a reactor volume of 5,000,000 m^3 is needed to completely capture CO_2 from a 160 MW power plant

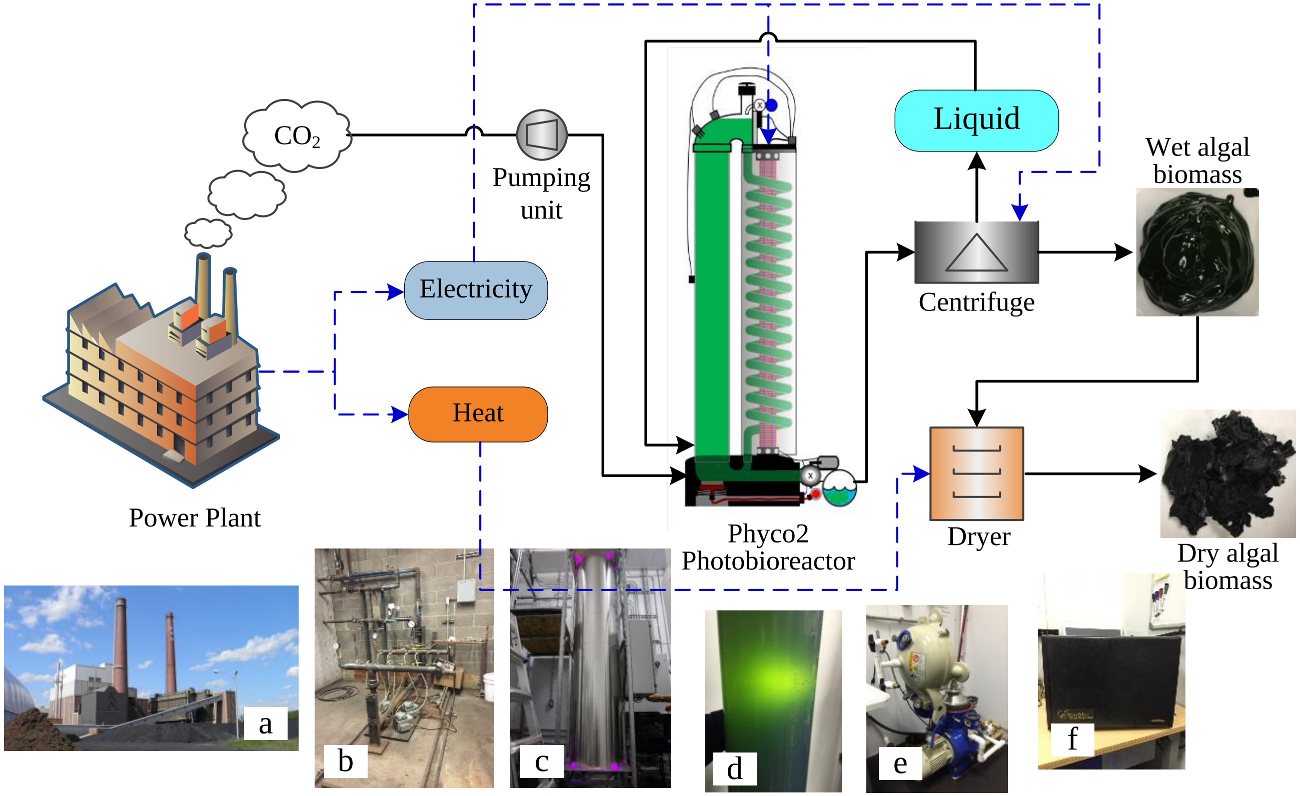
Large footprint of algal cultivation

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

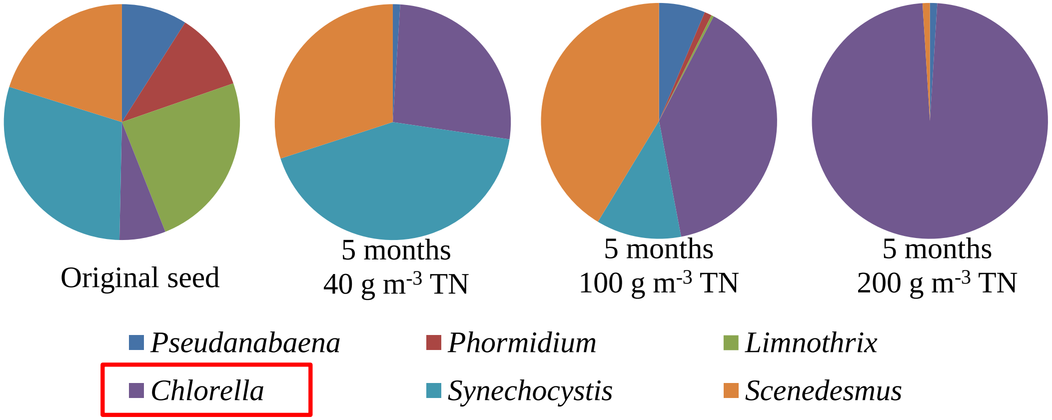
a. T.B. Simon power plant; b. Flue gas pumping unit; c. Photobioreactor; d. Algae growing in the reactor; e. Centrifuge; f. Dryer

Scientific and Technical Merit

Previous studies and supportive data

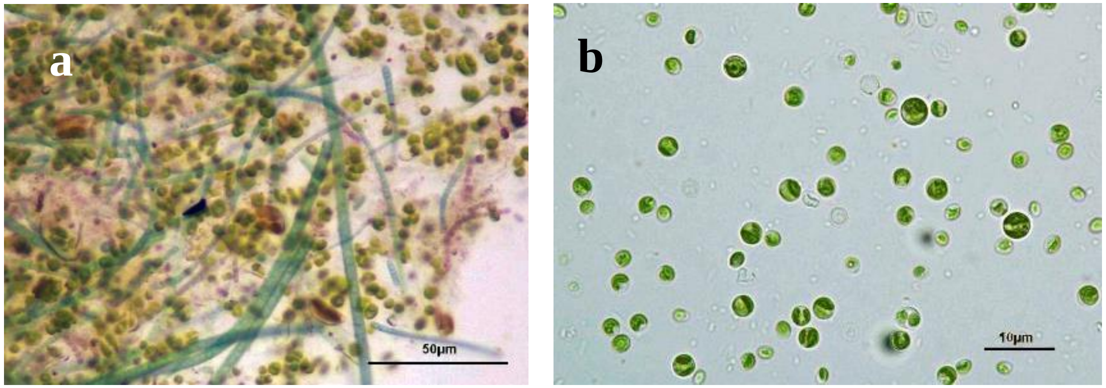
1. A robust algal strain from Great lake region

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

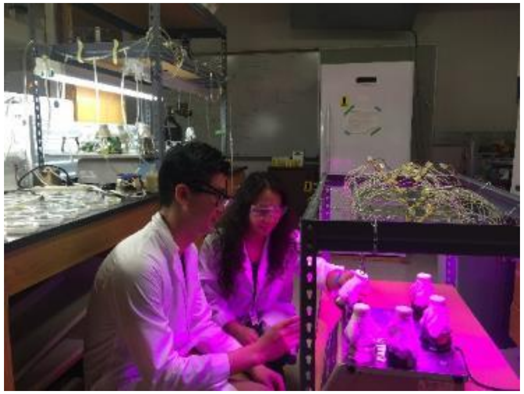


Changes of the algal assemblage during 5 months continuous culture

Flask culture (250 ml)



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



Effects of different wavelengths on algae

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

Properties	value
Crude proteins (% dry biomass)	47.3 ± 0.9
Lipids (% dry biomass)	10.6 ± 1.8
Carbohydrates (% dry biomass)	36.6 ± 0.8
Ash (% dry biomass)	8.4 ± 1.0

Amino acid profile of the algal biomass

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

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

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

*: 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; CFPP represents cold filter plugging point; and DU represents degree of unsaturation.

Methane production of anaerobic digestion of algal biomass residues

Algal biomass residues loading ratio (%)	Animal manure loading ratio (%)	Specific methane yield (L CH_4/g VS/d)	Volumetric productivity (L CH_4/L/d)
50	50	0.54	1.62
0	100	0.41	1.10

Characteristics of polyurethane foam from algal protein

	Polyurethane foam
Core density (kg/m^3)	40
Compressive strength (kPa)	165
Resiliency (%)	55
Elongation (%)	50

Scientific and Technical Merit

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

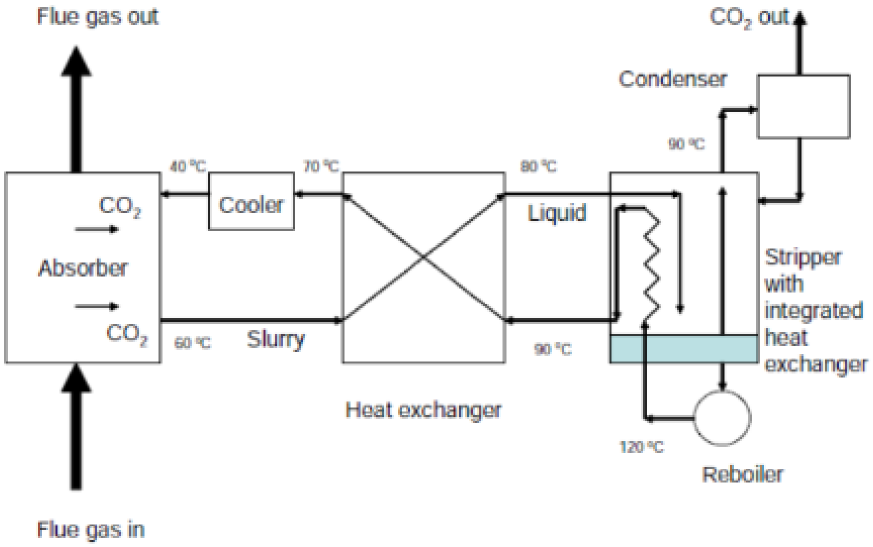
Chemical reactions of amino acid salt CO_2 absorption*

Amine formation: $\underset{\text{amino acid}}{{}^{-}OOC\text{-}R\text{-}NH_3^{+}} + KOH \rightarrow K+ + \underset{\text{amine}}{{}^{-}OOC\text{-}R\text{-}NH_2} + H_2O$

Carbamate formation: $CO_2 + 2\,{}^{-}OOC\text{-}R\text{-}NH_2 \leftrightarrow \underset{\text{carbamate}}{{}^{-}OOC\text{-}R\text{-}NH\text{-}COO^{-}} + {}^{-}OOC\text{-}R\text{-}NH_3^{+}$

Carbamate hydrolysis: ${}^{-}OOC\text{-}R\text{-}NH\text{-}COO^{-} + H_2O \leftrightarrow {}^{-}OOC\text{-}R\text{-}NH_2 + \underset{\text{bicarbonate}}{HCO_3^{-}}$

Biocarbonate formation: $CO_2 + {}^{-}OOC\text{-}R\text{-}NH_2 + H_2O \leftrightarrow {}^{-}OOC\text{-}R\text{-}NH_3^{+} + HCO_3^{-}$



Absorption and stripping process of using amino acid salt*

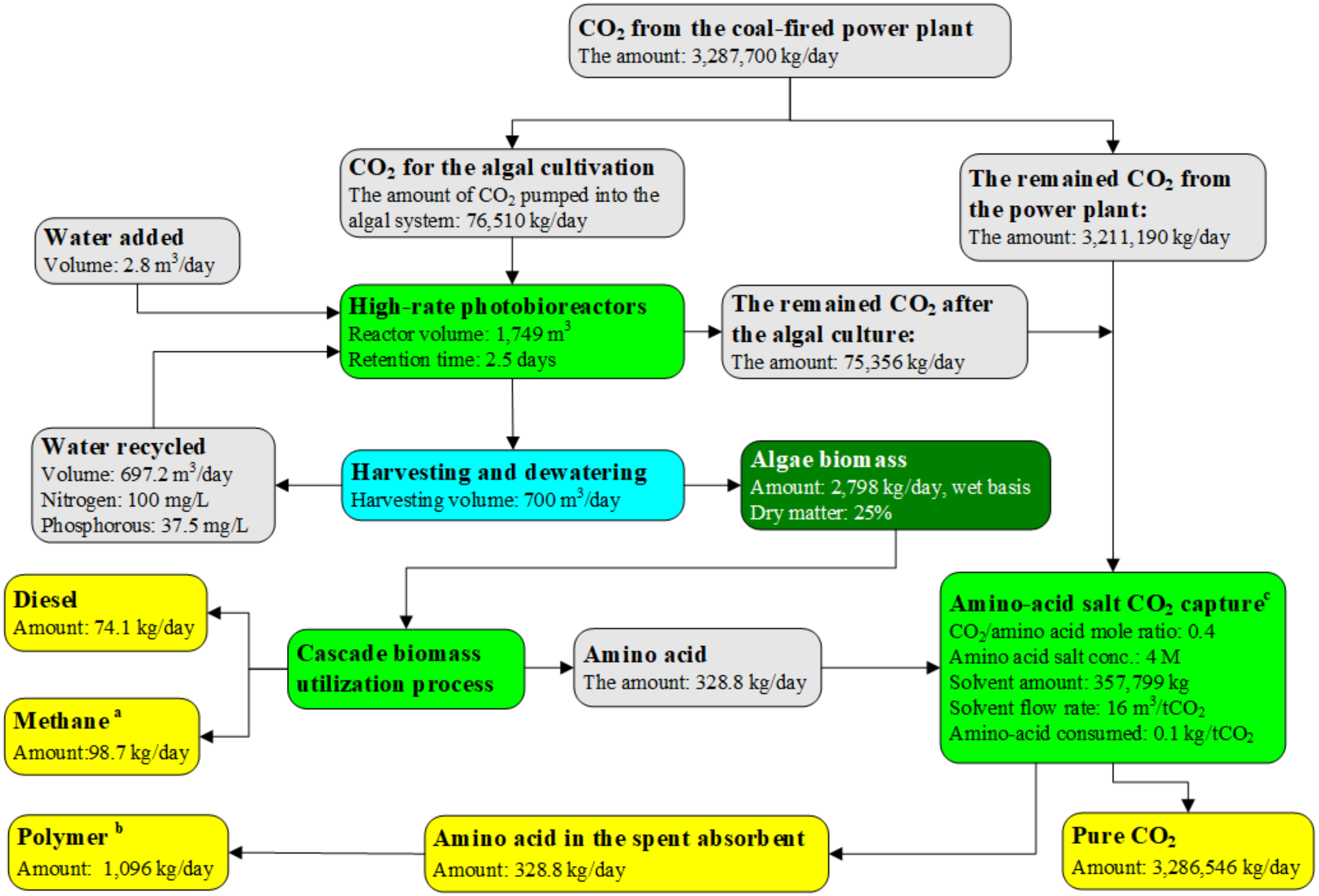
*: From: J.P. Brouwer, TNO Science & Industry, The Netherlands

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 CO_2, 6,000 metric tons of N_2O, and 3,000 metric tons of SO_2 per year.



CO_2 from the coal-fired power plant
The amount: 3,287,700 kg/day

CO_2 for the algal cultivation
The amount of CO_2 pumped into the algal system: 76,510 kg/day

The remained CO_2 from the power plant:
The amount: 3,211,190 kg/day

Water added
Volume: 2.8 m^3/day

High-rate photobioreactors
Reactor volume: 1,749 m^3
Retention time: 2.5 days

The remained CO_2 after the algal culture:
The amount: 75,356 kg/day

Water recycled
Volume: 697.2 m^3/day
Nitrogen: 100 mg/L
Phosphorous: 37.5 mg/L

Harvesting and dewatering
Harvesting volume: 700 m^3/day

Algae biomass
Amount: 2,798 kg/day, wet basis
Dry matter: 25%

Diesel
Amount: 74.1 kg/day

Cascade biomass utilization process

Amino acid
The amount: 328.8 kg/day

Amino-acid salt CO_2 capture[c]
CO_2/amino acid mole ratio: 0.4
Amino acid salt conc.: 4 M
Solvent amount: 357,799 kg
Solvent flow rate: 16 m^3/tCO_2
Amino-acid consumed: 0.1 kg/tCO_2

Methane[a]
Amount:98.7 kg/day

Polymer[b]
Amount: 1,096 kg/day

Amino acid in the spent absorbent
Amount: 328.8 kg/day

Pure CO_2
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 generates14,416,457 GJ/year for both electricity and heat.

System components	Energy value (GJ/year)		
	The proposed system [b]	The amino acid salt process [c]	MEA process [d]
Chemical production			
Energy input	-2,184	-52,805	-246
Energy output	2,920	-	-
CO_2 capture			
Energy input	-2,759,055	-2,759,055	-5,040,044
Energy output	-	-	-
Total energy input	-2,761,389	-	-5,040,290
Total energy output	1,920	-	-
Net energy	**-2,759,469**	**-2,811,860**	**-5,040,290**

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 CO_2 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 CO_2 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.

System components [a]	**The proposed system** [b]	**The amino acid salt process** [c]	**MEA process** [d]
Operational cost ($/year)	-400,000	-360,036	-120,000
Income ($/year)	849,018	0	0
Revenue ($/year)	**449,018**	**-360,036**	**-120,000**

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 CO_2 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 CO_2 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 CO_2 capture and utilization).**

	The proposed system [b]	**The amino acid salt process [c]**	**MEA process [d]**
Greenhouse gas release from the chemical production (metric ton CO_2-e per year) [a]	**-421**	**648**	**171.6**

a. The positive numbers mean greenhouse gas release. The negative number means greenhouse gas reduction.

b. The algal culture uptakes 1,154 kg CO_2/day.

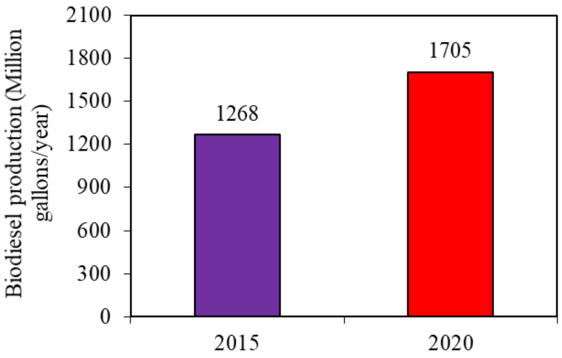
c. The CO_2-e for amino acid production is 5.4 kg CO_2-e per kg amino acid. The amount of amino acid required by the process is 120,012 kg/year.

d. The CO_2-e for MEA production is 171,600 kg per year based on the amount of fossil carbon used to manufacture MEA.

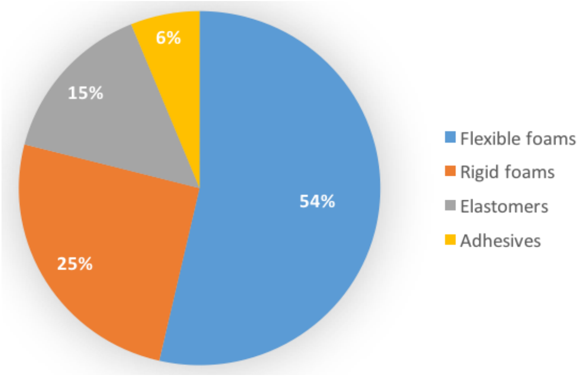
Scientific and Technical Merit

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.



U.S. biodiesel production



Global polyurethane market sectors

	Production (metric ton/year)	Unit price ($/kg)
Glutamic acid	1,000,000	5
Lysine	350,000	3
Methionine	250,000	3

Global amino acid market

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.

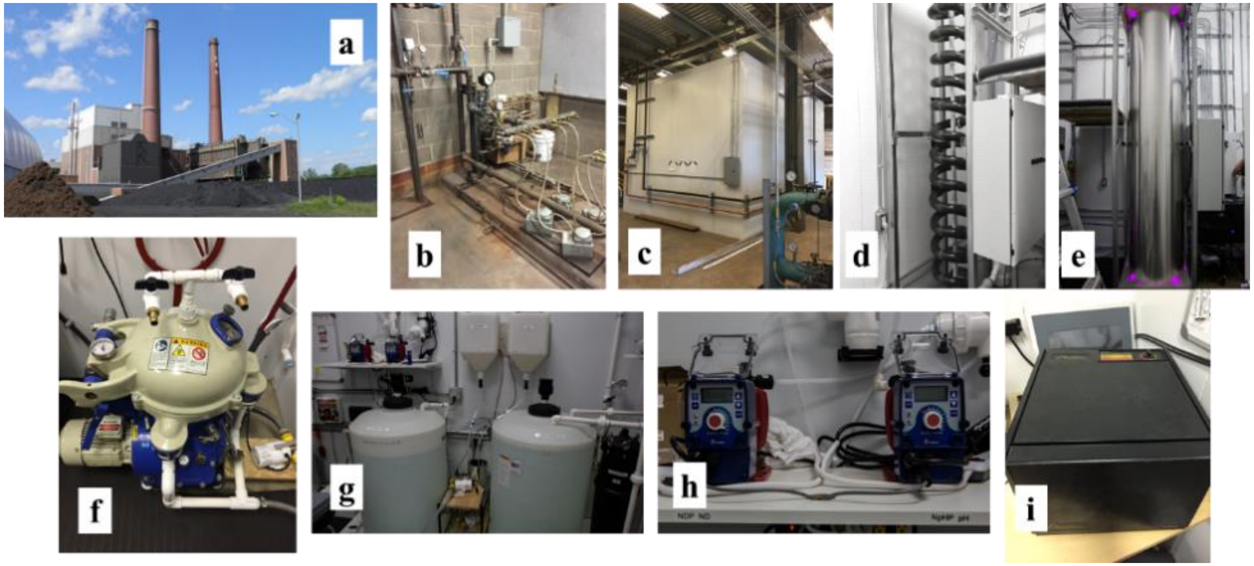
- Brief quarterly progress reports will be developed and submitted.

- 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.

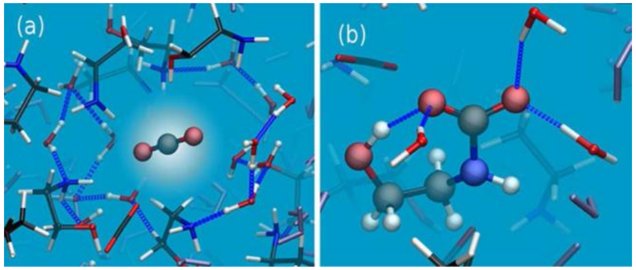
Technical Approach

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 CO_2 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.

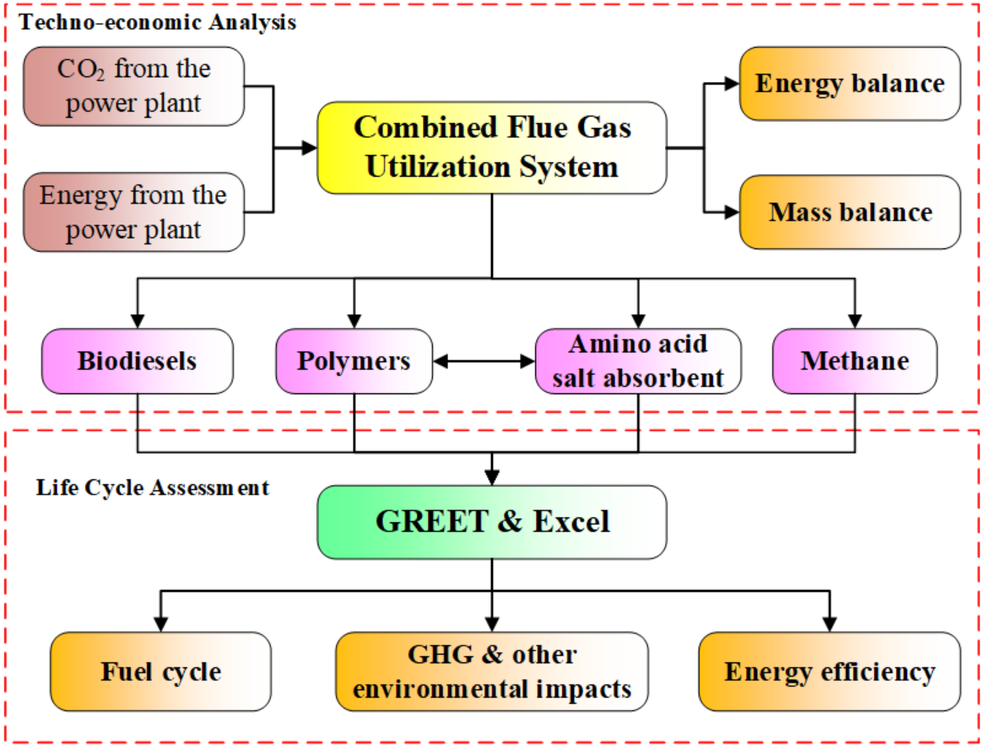


Molecular dynamic simulation (a) before and (b) after formation of carbamate. From: Ma, C et al. 2014. J. Phys. Chem. Lett. 5. 1672-1677

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.



Techno-economic Analysis

CO_2 from the power plant

Energy from the power plant

Combined Flue Gas Utilization System

Energy balance

Mass balance

Biodiesels

Polymers

Amino acid salt absorbent

Methane

Life Cycle Assessment

GREET & Excel

Fuel cycle

GHG & other environmental impacts

Energy efficiency

Procedure of TEA and LCA

Technical Approach

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.

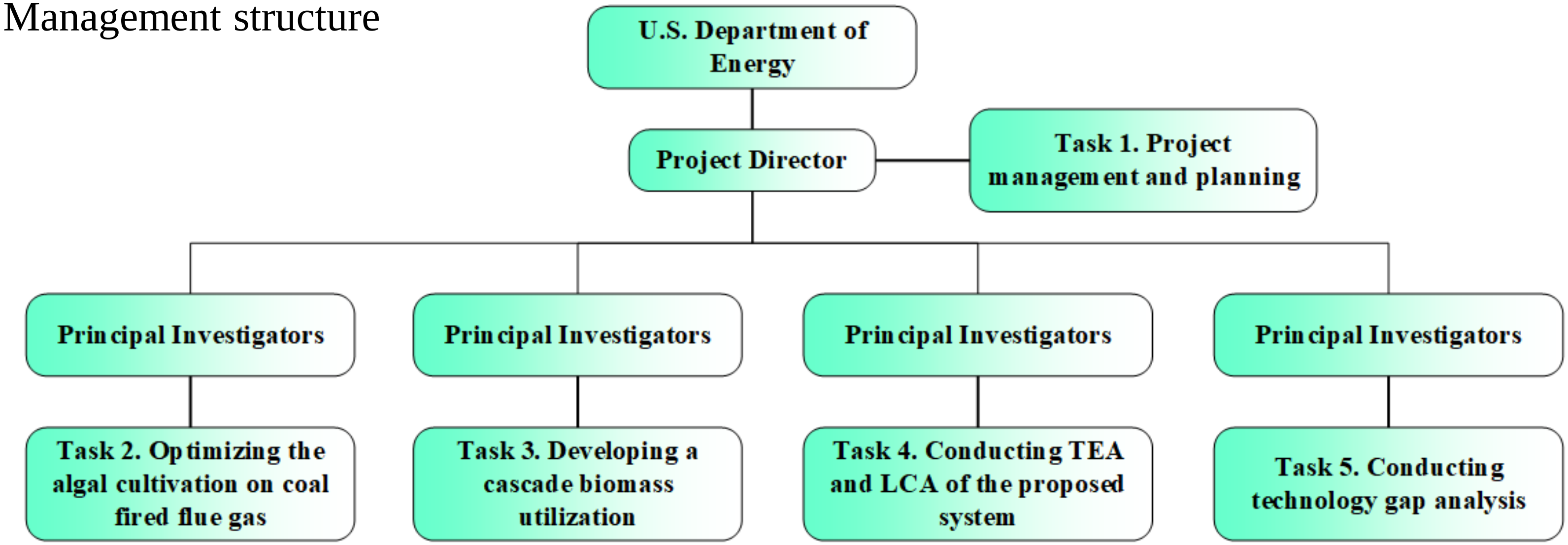
- Experimental plan:
  - The data from the previous TEA will be used for the technology gap analysis.
  - A control operation (power plant with algal biofuel production) will be used as the baseline.
  - Sensitivity analysis will be used to identify the key technologies (unit operations) that limit the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

Detailed Project Management Plan

Management structure and responsibilities

- Management structure


U.S. Department of Energy

Project Director

Task 1. Project management and planning

Principal Investigators

Task 2. Optimizing the algal cultivation on coal fired flue gas

Principal Investigators

Task 3. Developing a cascade biomass utilization

Principal Investigators

Task 4. Conducting TEA and LCA of the proposed system

Principal Investigators

Task 5. Conducting technology gap analysis

- 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

Detailed Project Management Plan

Risk management

- Potential risks and mitigation plans

Risk type	Risk Level	Impact	Mitigation
Technical risks			
pH drop	Low	Slow algal growth and low biomass productivity	A pH feedback loop will be installed to control the CO_2 feeding rate.
Biofilm formation	Medium	Reduced photosynthesis efficiency	Rubber string balls will be added into the reactor to clean up the biofilm.
Process complexity of cascade conversion	High	Unfavorable mass and energy balance	Simplifying individual unit operations in the cascade conversion process could alleviate the negative impact of process complexity.
Management risk			
Steady flue gas supply	Low	Flue gas shut down due to the maintenance	Gas cylinders will be used as a backup flue gas flow to support the algal culture system.

Detailed Project Management Plan

Project timeline and milestones

				Budget period 1 (10/1/2017-9/30/2018)				**Budget period 2** (10/1/2018-9/30/2019)				**Budget period 3** (10/1/2019-9/30/2020)			
				Quarter				Quarter				Quarter			
Tasks	**Start Date**	**End date**	**Cost**	1	2	3	4	1	2	3	4	1	2	3	4
1.0 – Project management and planning	10/1/2017	9/30/2020		▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
1.1 – Project management and planning				▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
1.2 – Briefings and reports				▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Milestones															
Kick-off meeting presentation				◊											
Quarterly progress report				◊	◊	◊	◊	◊	◊	◊	◊	◊	◊	◊	◊
Annual report							◊				◊				◊
Final report															◊
2.0 – Optimizing the photobioreactor operation	10/1/2017	9/30/2019		▨	▨	▨	▨	▨	▨	▨	▨				
Milestones															
pH is stable at 6.5 at the flue gas rate of 120 L/min							◊								
No bacterial contamination in 12 months operation							◊								
Algal biomass concentration reaches 1.2 g/L											◊				
Algal biomass productivity reaches 0.5 g/L/day											◊				
The optimal culture conditions are concluded											◊				

				Budget period 1 (10/1/2017-9/30/2018)				**Budget period 2** (10/1/2018-9/30/2019)				**Budget period 3** (10/1/2019-9/30/2020)			
				Quarter				Quarter				Quarter			
Tasks	**Start Date**	**End date**	**Cost**	1	2	3	4	1	2	3	4	1	2	3	4
3.0 – Developing a cascade conversion process	10/1/2017	9/30/2020		▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
3.1 – High-efficiency protein extraction	10/1/2017	9/30/2018		▨	▨	▨	▨								
3.2 – Optimization of mixed amino acid solution	10/1/2018	9/30/2020						▨	▨	▨	▨	▨	▨	▨	▨
3.3 – One-pot syntheses of biopolyol	10/1/2018	9/30/2020						▨	▨	▨	▨	▨	▨	▨	▨
Milestones															
Amino acid yield reaches 90% of the algal protein							◊								
Mixed amino acid salt solution has a absorption capacity of 0.5 mole CO_2/mole amino acid salt											◊				
The spend amino acid solution can be converted to biopolyol at a conversion of 80%															◊
With biodiesel and methane production, cascade conversion can achieve 100% of algal biomass utilization (not counting ash)															◊
4.0 – Conducting TEA and LCA	10/1/2019	9/30/2020										▨	▨	▨	▨
Milestones															
A detailed TEA on a full scale system based on a 160 megawatts coal-fired power plant will be delivered.															◊
A detailed LCA on a full scale system based on a 160 megawatts coal-fired power plant will be delivered															◊
5.0 – Technology gas analysis	10/1/2019	9/30/2020										▨	▨	▨	▨
A detailed summary of R&D gaps will be delivered															◊

Detailed Project Management Plan

Milestone log

Budget period	ID	Task number	Milestone description	Planned completion date	Actual completion date	Verification method
1	1	1	Kick-off meeting	10/23/2017		Meeting presentation
1, 2, 3	2	1	Quarterly progress report	The end of each quarter		Project management plan
1, 2, 3	3	1	Annual report	The end of each budget period		Project management plan
3	4	1	Final report	9/30/2020		Project management plan
1	5	2	pH is stable at 6.5 at the flue gas rate of 120 L/min	9/30/2018		Annual report
1	6	2	No bacterial contamination in 12 months operation is achieved	9/30/2018		Annual report
2	7	2	Algal biomass concentration reaches 1.2 g/L	9/30/2019		Annual report
2	8	2	Algal biomass productivity reaches 0.5 g/L/day	9/30/2019		Annual report
2	9	2	The optimal culture conditions are concluded	9/30/2019		Annual report
1	10	3	Amino acid yield reaches 90% of the algal protein	9/30/2018		Annual report
2	11	3	Mixed amino acid salt solution has a absorption capacity of 0.5 mole CO_2/mole amino acid salt	9/30/2019		Annual report
3	12	3	The spend amino acid solution can be converted to biopolyol at a conversion of 80%	9/30/2020		Annual report
3	13	3	With biodiesel and methane production, cascade conversion can achieve 100% of algal biomass utilization (not counting ash)	9/30/2020		Annual report
3	14	4	A detailed TEA on a full scale system based on a 160 megawatts coal-fired power plant will be delivered.	9/30/2020		Annual report
3	15	4	A detailed LCA on a full scale system based on a 160 megawatts coal-fired power plant will be delivered	9/30/2020		Annual report
3	16	5	A detailed summary of R&D gaps will be delivered	9/30/2020		Annual report/Final report

Detailed Project Management Plan

Project go/no-go decision point

Decision point (DP)	Date	Success criteria
DP 1. Continuous culture of the photobioreactor	8/15/2018	- Achieving the long-term stability of algal culture will be achieved (around 8-9 month continuous culture without any contamination issues)
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 CO_2 capture capacity of 0.5 mole CO_2/mole amino acid solution

Project Budget

Budget period	Fiscal year	Performer	Federal cost ($)	Non-federal cost share ($)	Total cost ($)
1	FY17	MSU	275,110	86,890	362,000
2	FY18	MSU	281,957	55,705	337,662
3	FY19	MSU	292,921	78,787	371,708
1	FY17	PHYCO2	127,765	19,053	146,818
2	FY18	PHYCO2	15,445	19,053	34,498
3	FY19	PHYCO2	6,775	9,526	16,301
			999,976	269,014	1,268,990

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/

Go Green !!