A Microalgae-based Platform for the Beneficial Reuse of CO_2 Emissions from Power Plants

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Project Overview

- **Funding:**
  DOE: $990,334
  Cost share: $261,110
  Total project: $1,251,444

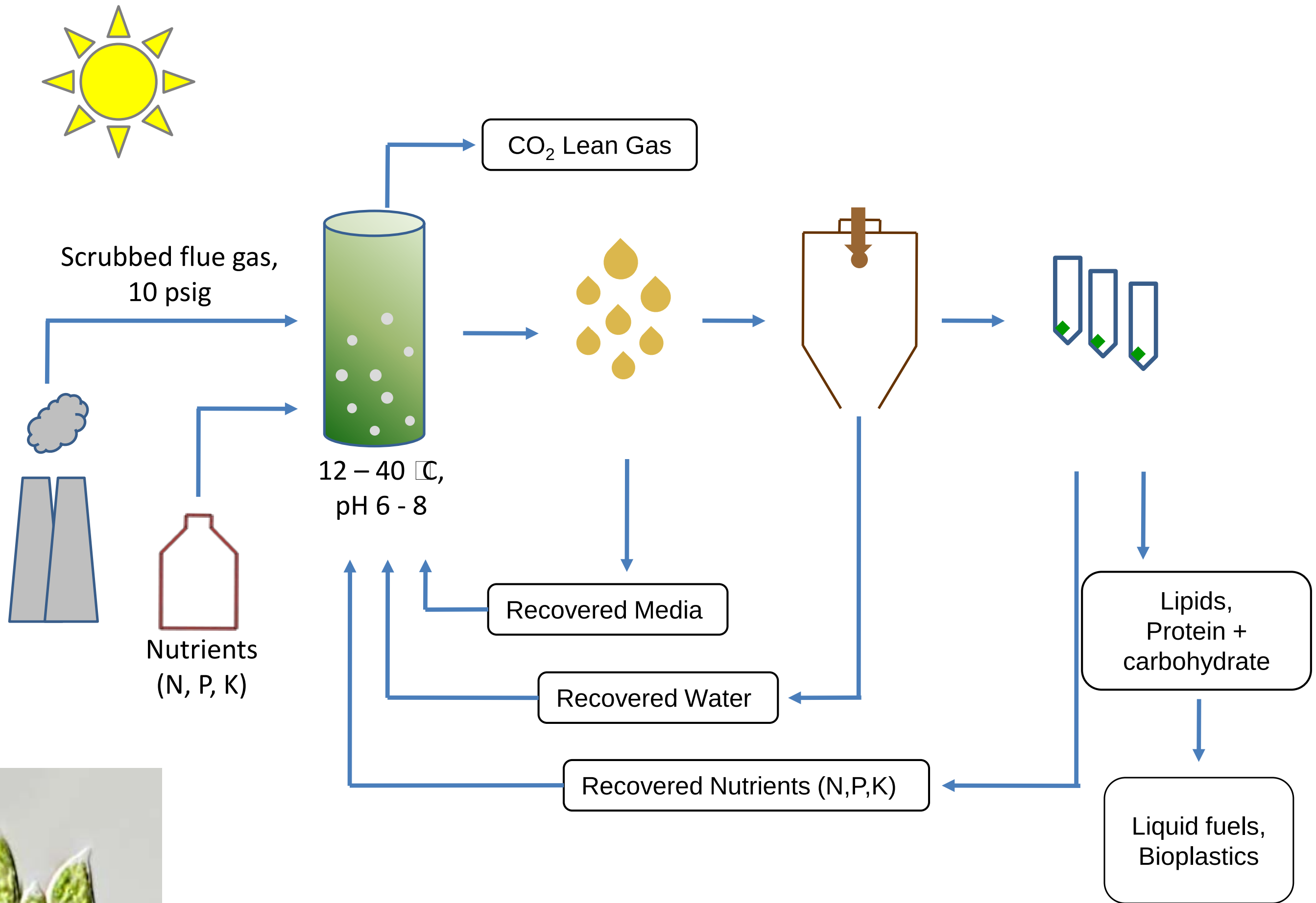
- **Performance dates:**
  10/1/2015 – 9/30/2017

- **Project Participants:**
  - University of Kentucky
  - University of Delaware
  - Algix LLC
  - Duke Energy

Project Objectives:

- Optimize UK's technology for microalgae cultivation and processing with respect to cost and performance, particularly with regard to harvesting and dewatering
- Develop strategies to monitor and maintain algae culture health
- Develop a biomass utilization strategy which produces lipids for upgrading to fuels and a proteinaceous feedstock for the production of algal-based bioplastics
- Perform techno-economic analyses to calculate the cost of CO_2 capture and recycle, and life cycle analyses to evaluate the GHG emission reduction potential.

Simplified Process Schematic



Scenedesmus acutus

Large-Scale Algae Cultivation

Open Ponds:

- Relatively low capital cost
- Mature technology
- Operationally simple

- Large area requirements
- Significant evaporative losses
- Subject to contamination
- Low CO_2 utilization efficiency

Photobioreactors:

- Higher yield of biomass per unit area
- Low water loss
- Lower risk of culture contamination
- Can be further optimized?

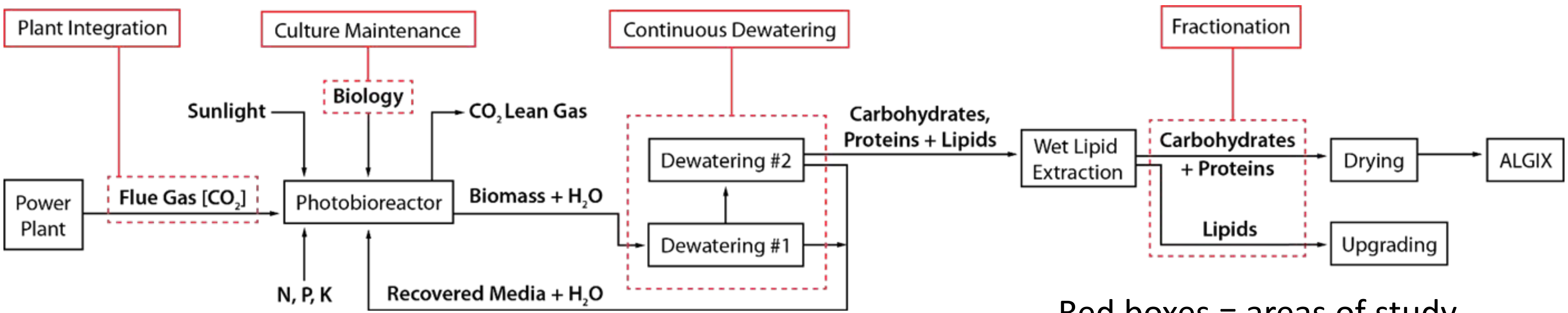
- High capital cost
- Technology is not mature
- Operational costs?

Advantages and Challenges

- ➢ Ability to generate a valuable product, thereby off-setting costs of CO_2 capture (potential for new industry)
- ➢ No need to concentrate CO_2 stream
- ➢ Potential to polish NOx and SOx emissions

- Areal productivity such that very large algae farms required for significant CO_2 capture
- CO_2 capture efficiency modest (<50%)
- Challenging economics: cost of algae cultivation is high (currently >$1,000/MT), hence require medium to high value applications for produced algae biomass
- Market size generally inversely related to application value (hence risk of market saturation)

Technical Approach/Project Scope

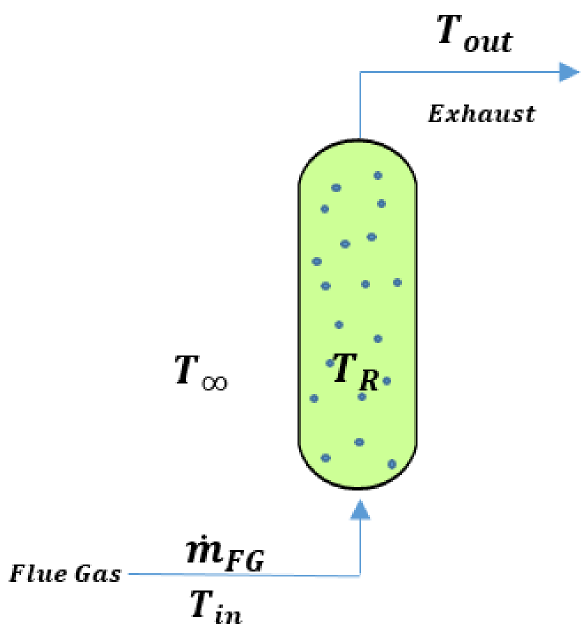


Red boxes = areas of study

Year 1:

- Task 1: Project Management (all)
- Task 2: Engineering Analysis & Testing (UK):
  - PBR/power plant heat integration assessment
  - design, construction and lab testing of continuous algae dewatering system
  - operation and field testing of PBR + dewatering system
- Task 3: System Biology (UD):
  - plant outage mitigation system design
  - effect of flue gas constituents on biomass composition
- Task 4: Biomass Valorization/Utilization (UK/Algix)
  - lipid extraction from wet algae biomass
  - characterization of production biomass
  - bioplastic formulation

Engineering Analysis & Testing (Task 2): Heat Transfer Model for Photobioreactor Modeled as a Single Tube



$$Q_{Total} = m_R C p_R \left(\frac{dT_R}{dt}\right) = Q_1 + Q_2 + Q_3$$

$$Q_1 = UA(T_R - T_\infty)$$

$$Q_2 = \dot{m}_{FG} C p_{FG} (T_{in} - T_{out})$$

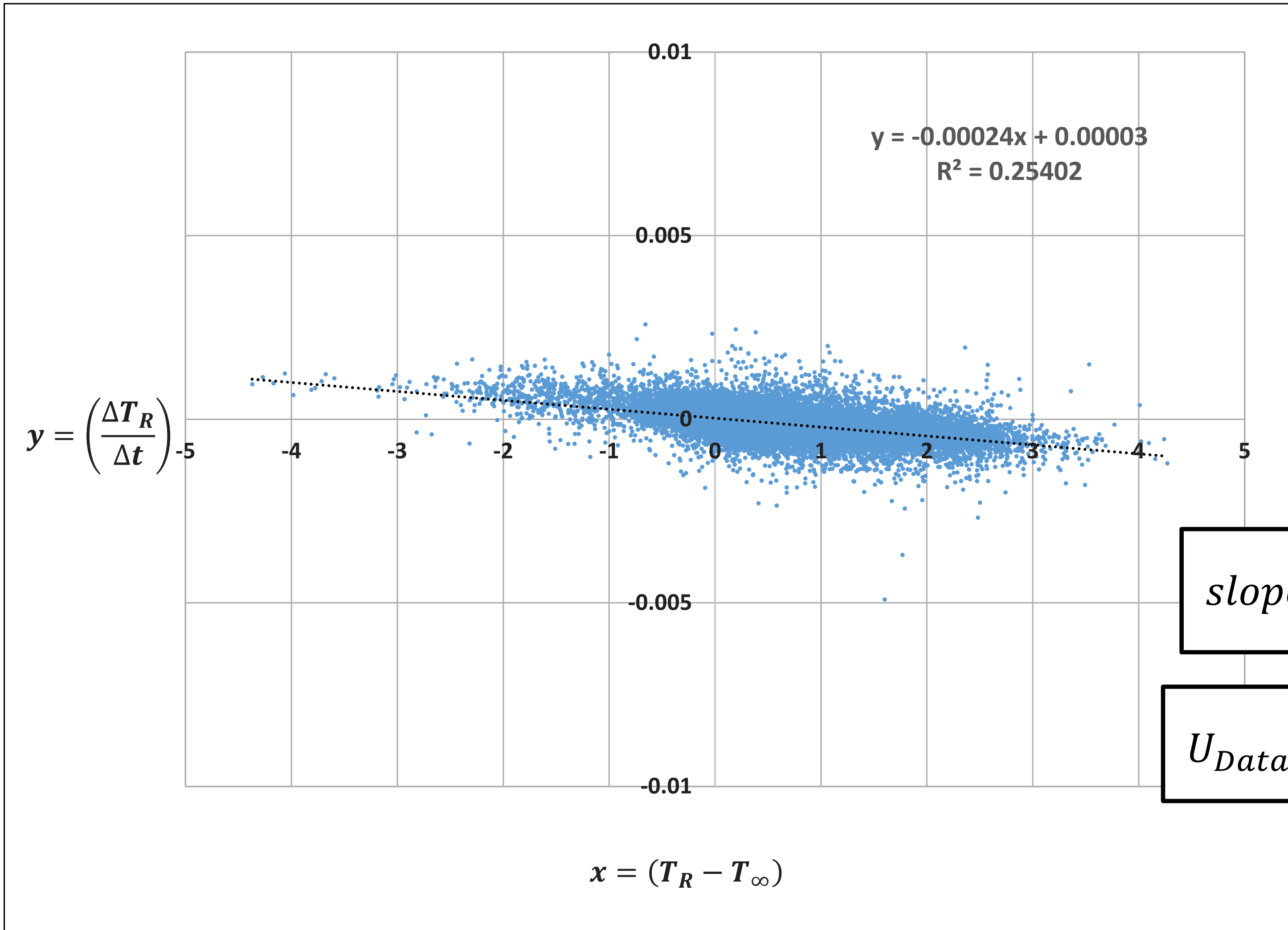
$$Q_3 = \dot{m}_{FG} \lambda_{H_2O} (y_{H2O_{IN}} - y_{H2O_{OUT}})$$

$$If\ T_R\ is\ constant \rightarrow Q_1 = Q_2 = Q_3$$

$$If\ T_R \neq constant \rightarrow m_R C p_R \left(\frac{dT_R}{dt}\right) = Q_1 + Q_2 + Q_3$$

$$U = \left[\left(\frac{1}{h_{H_2O} A_i}\right) + \left(\frac{\ln\left(\frac{r_o}{r_i}\right)}{2\pi K_{PET} L}\right) + \left(\frac{1}{h_{air} A_o}\right)\right]^{-1}$$

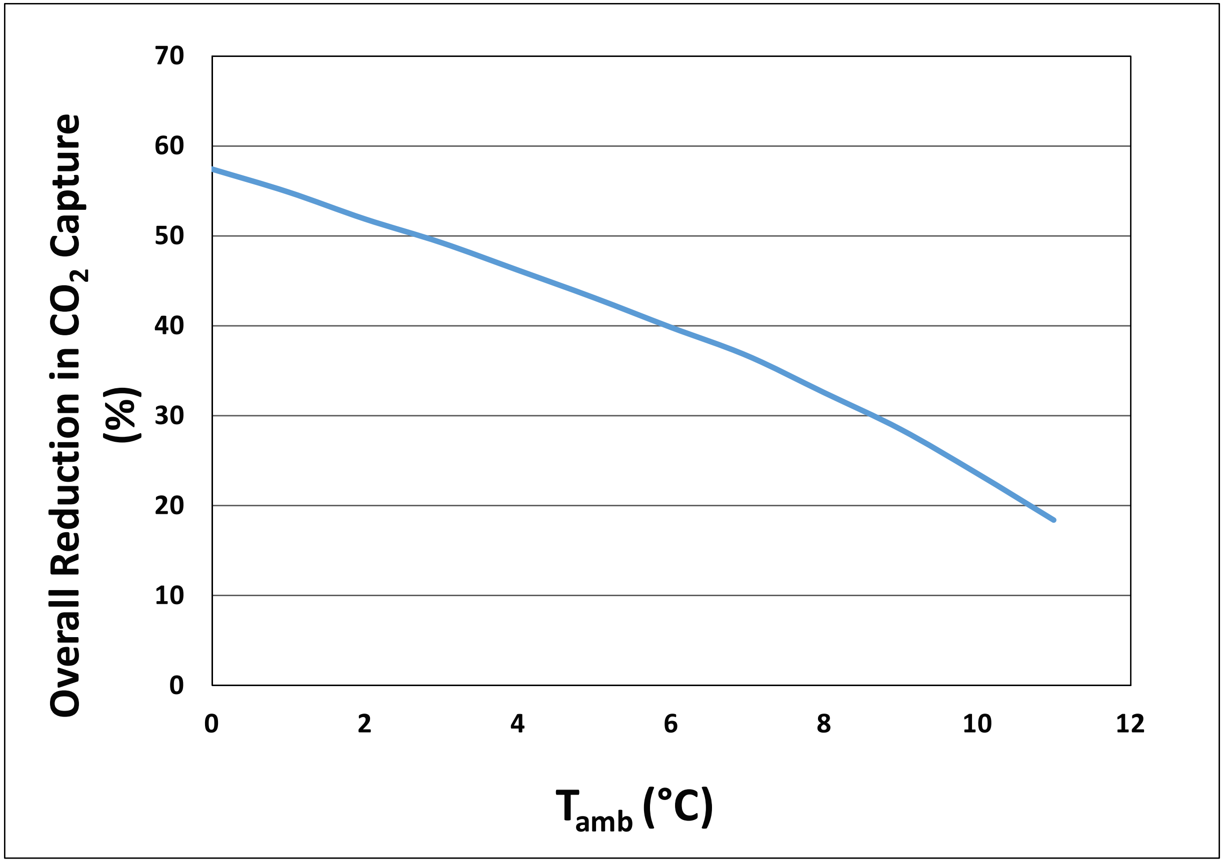
Experimental Determination of U (Overall Heat Transfer Coefficient) using Data from 2015 Growing Season (May-Sep)



$$slope = \frac{UA}{m_R Cp_R}$$

$$U_{Data} = 23.8 \frac{W}{m^2 K}$$

Reduction in Overall CO_2 Capture vs. Ambient Temperature

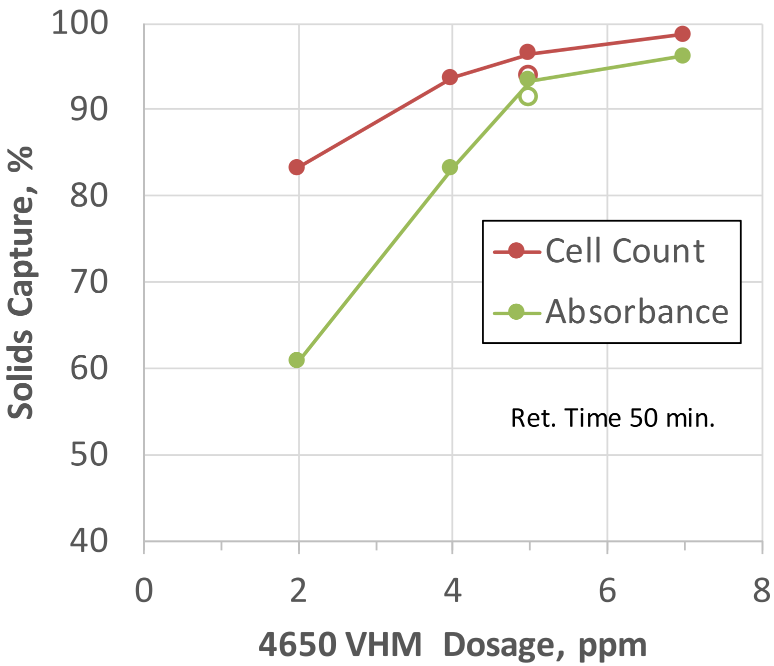


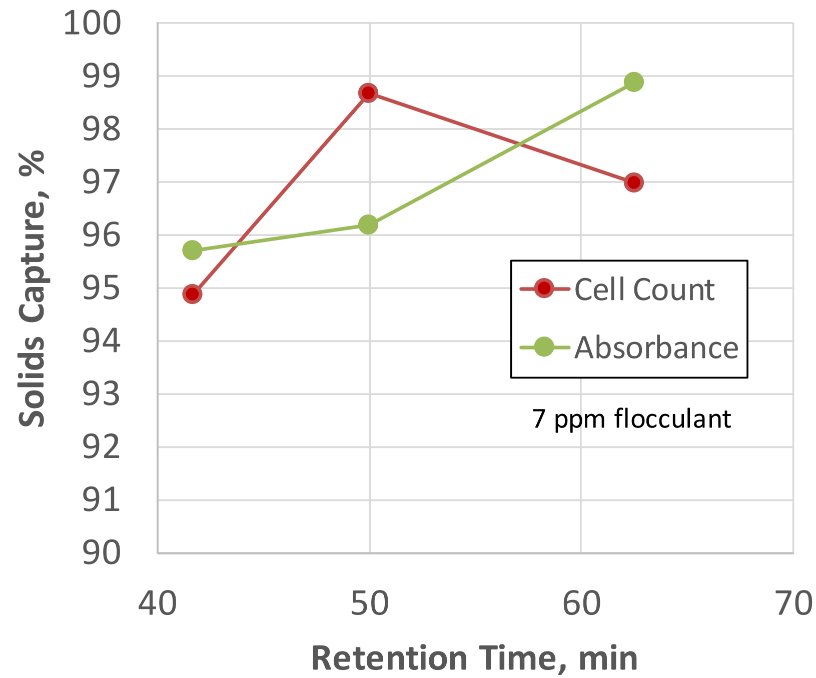
- Assumptions: 30% CO_2 capture from a 1 MW coal-fired power plant
- Heat source = boiler water (910,000 L/min, T = 32-45 ^{0}C)
- Increased CO_2 emissions arise from pumping boiler water to PBR heat exchanger and increased cycling of PBR culture through heat exchanger

Continuous Thickener Prototype

- 25 L lamella thickener: conical-shaped settling chamber to promote biomass compaction; 11 lamella plates inclined at 45° to provide settling surface for residual solids
- Overflow analyzed for residual solids (cytometer, UV-vis spectrophotometer)

Effect of Dosage





Note: Filled data points denote batch flocculant addition
Open data points denote continuous flocculant addition

- 95% solids recovery using 7 ppm flocculant and retention time of 50 min
- Results for continuous flocculant addition also promising

East Bend Station Demonstration Facility

DUKE ENERGY®

650 MW Scrubbed Unit (SCR, FGD, ESP)

MAIN GOALS

- Define kinetics of process
  - Monitor dissolved CO_2 and O_2 to determine photosynthetic rate
  - Help size large system and next generation design
- Gain understanding of real capital and operating costs
  - Minimize energy consumption
- Measure biomass composition to track heavy metals and other flue gas constituents

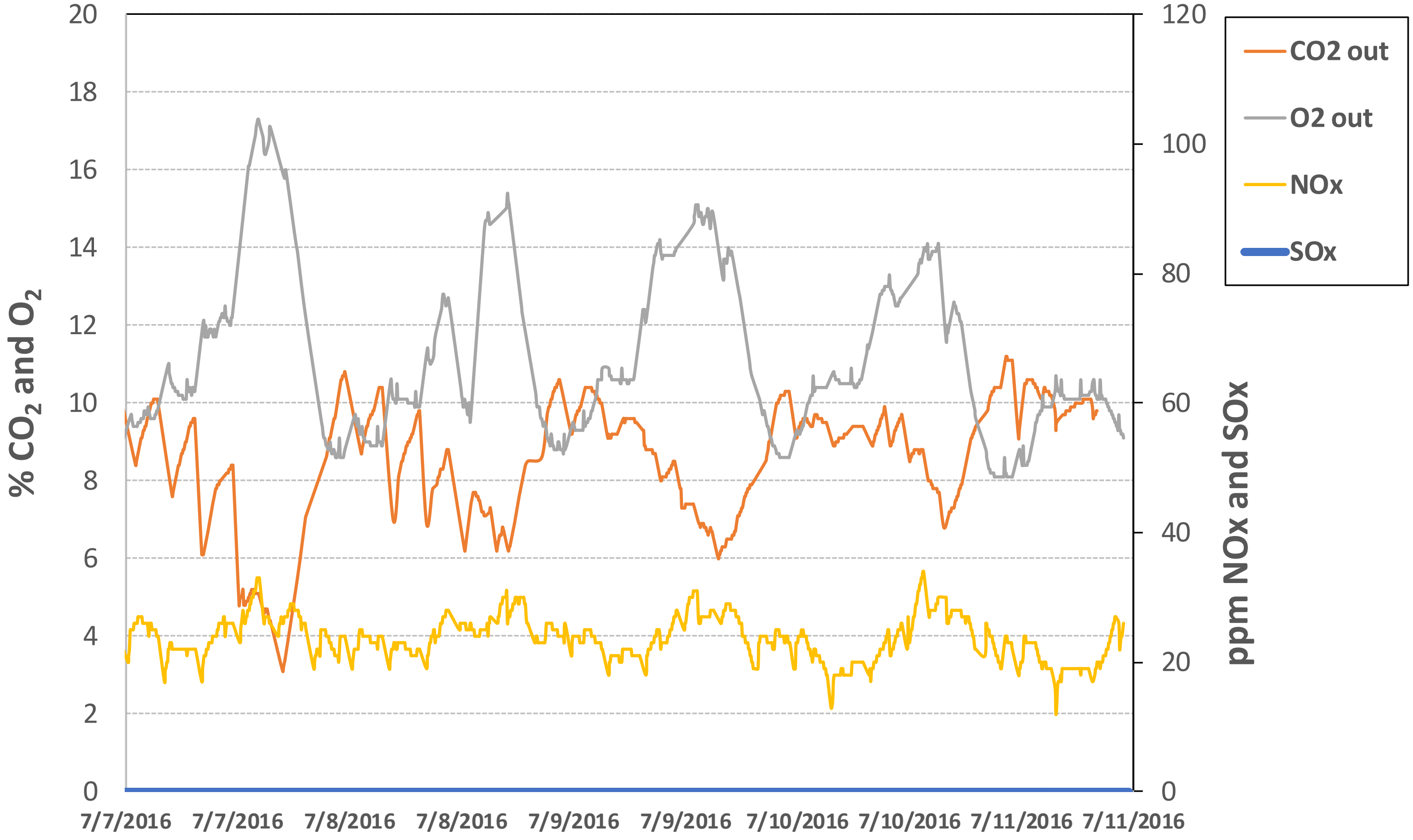
	CO_2 %	NO_x ppm	SO_2 ppm
Average	8.9	53.4	28.0
Minimum	7.2	14.5	6.5
Max.	9.6	97.2	84.3

East Bend Station: Field Testing

- Flue gas injection system updated with updated regulator, flow meter/totalizer, and pressure gauges

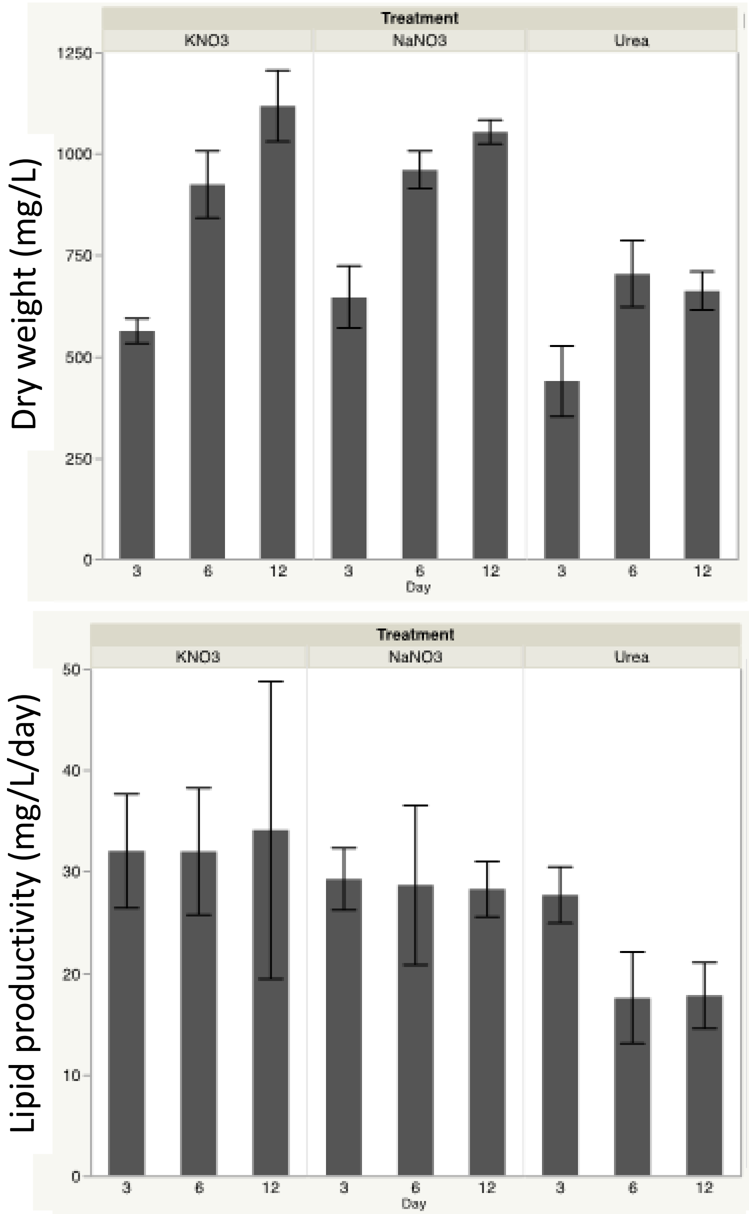
- Improved PBR installed at East Bend, along with updated control and data tracking system
- PBR inoculated in mid-June
- Strong algae growth observed; one plant outage and one lightning strike to date!

Gas Analysis at Photobioreactor Outlet



- O_2 production correlates with CO_2 consumption
- Complete SOx removal from flue gas; ca. 50% NOx removal

System Biology (Task 3): Effect of N-Source with 9% CO_2



- N-source concentrations were set based on an equivalent price per L of media (0.13 g urea, 0.04 g of KNO_3, and 0.08 g $NaNO_3$ based on FOB prices)
- Lipid productivity was the same for nitrate grown cultures. However, both total achievable biomass and lipid productivity declined significantly for urea grown cultures after 6 and 12 days of growth.
- These results suggest that nitrate from the auto-oxidation of NOx at East Bend may be contributing significantly to the growth rates observed in the field.
- These results also support that nitrate supplementation could be economically feasible.

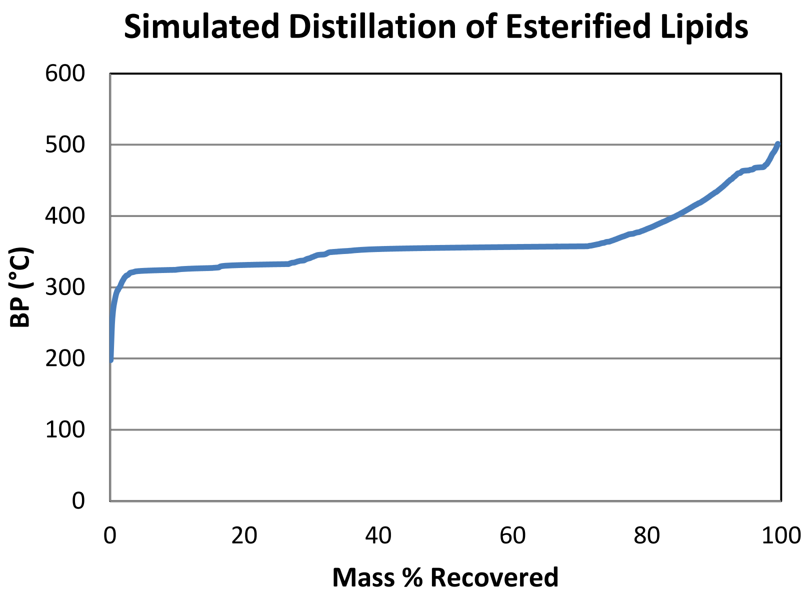
Biomass Utilization (Task 4):

Lipid Extraction

Raw algae slurry (g)	Recovered solids (g)	Recovered lipids (g)	Recovered mass (%)
1027.3 (+/-10.1)	156.2 (+/-10.2)	12.7 (+/-0.2)	84.0 (+/-4.7)

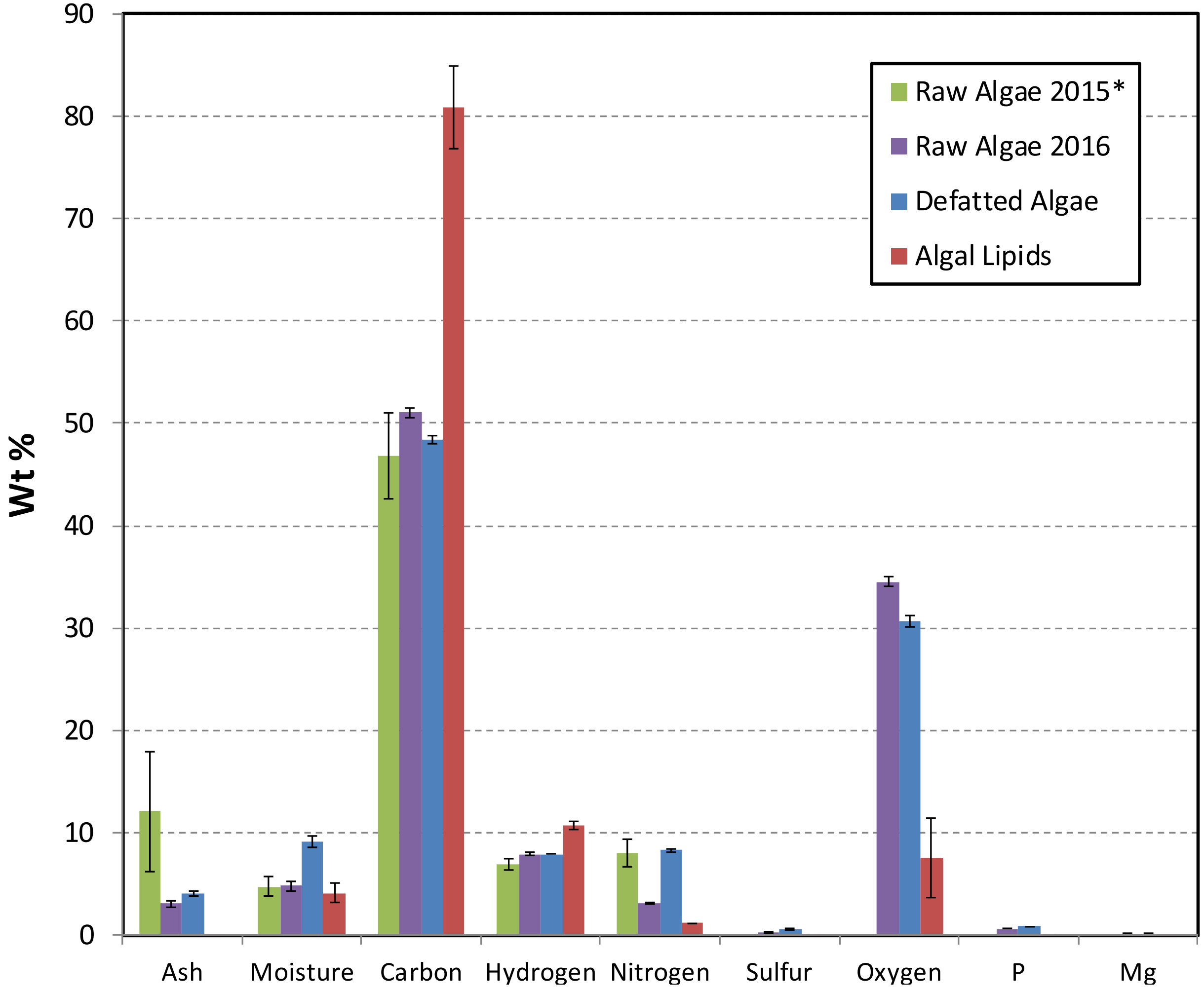
Average +/- st. dev. from 6 experiments

- Wet *Scenedesmus*, typically ~15 wt% solids
- Ultrasound, microwave irradiation and bead beating all proved ineffective for cell lysing
- Acidification to pH 1 using aq. HCl/MeOH results in cell lysing and simultaneous lipid (trans)esterification
- Yield of lipids = 6.3 (+/- 0.1) wt%, close to value reported previously for dry *Scenedesmus**



*E. Santillan-Jimenez, R. Pace, S. Marques, T. Morgan, C. McKelphin, J. Mobley, M. Crocker, *Fuel* 180 (2016) 668-678

Elemental Analysis of Whole and Defatted Algae



*S, O, Mg and P not measured

- High N content of defatted algae implies high protein content, confirmed by Algix (50.7% protein)
- Defatted algae showed significantly improved odor properties
- Bioplastic compounding studies in progress

Key Milestones / Success Criteria

Decision Point	Date	Success Criteria	Status
Lipid extraction	9/30/16	>50 wt% total lipid recovery demonstrated for wet extraction	>80% lipid recovery achieved
Demonstration of continuous dewatering	9/30/16	Solids recovery of >95% demonstrated	>95% solids recovery achieved
Verification of methodology for culture maintenance	9/30/17	Maintenance of culture viability for 2 weeks without flue gas	
Validation of bioplastic properties	9/30/17	Mechanical properties of bioplastics derived from defatted algae better or equal to bioplastics based on whole cell algae	
Lifecycle analysis	9/30/17	Lifecycle analysis shows net positive greenhouse gas emission reduction	

Summary

- Waste heat integration study completed
- Prototype continuous dewatering system designed, constructed and tested, with good results (>95% algae capture)
- Field testing at East Bend Station commenced
- Nutrient studies suggest strategies for increasing *Scenedesmus* productivity
- Method for lipid extraction from wet algae (10-15% solids) identified
- Lipid extraction scaled up (5 kg defatted algae produced for testing at Algix)

Future Work

- Nitrogen source experiments to be conducted using flue gas
- Plant outage experiments (cultures currently being acclimatized to flue gas conditions)
- Cyclic flow PBR operation at East Bend with collection of performance data for mass and energy balances
- Field testing of continuous dewatering system
- Bioplastic compounding studies using whole and defatted algae
- TEA and LCA

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University of Kentucky

University of Delaware

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