CO_2 to Bioplastics: Beneficial Re-use of Carbon Emissions from Coal-Fired Power Plants Using Microalgae

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Project Overview
(DE-FE0029632)

- **Funding:**
  DOE: $999,742
  Cost share: $258,720
  Total project: $1,258,462

- **Performance dates:**
  6/1/2017 – 5/31/2020

- **Project Participants:**
  - University of Kentucky
  - Colorado State U.
  - Algix LLC
  - Duke Energy

Project Objectives:

- A dual PBR/pond cultivation system will be evaluated with respect to capital and operational costs, productivity, and culture health, and compared to pond-only cultivation systems

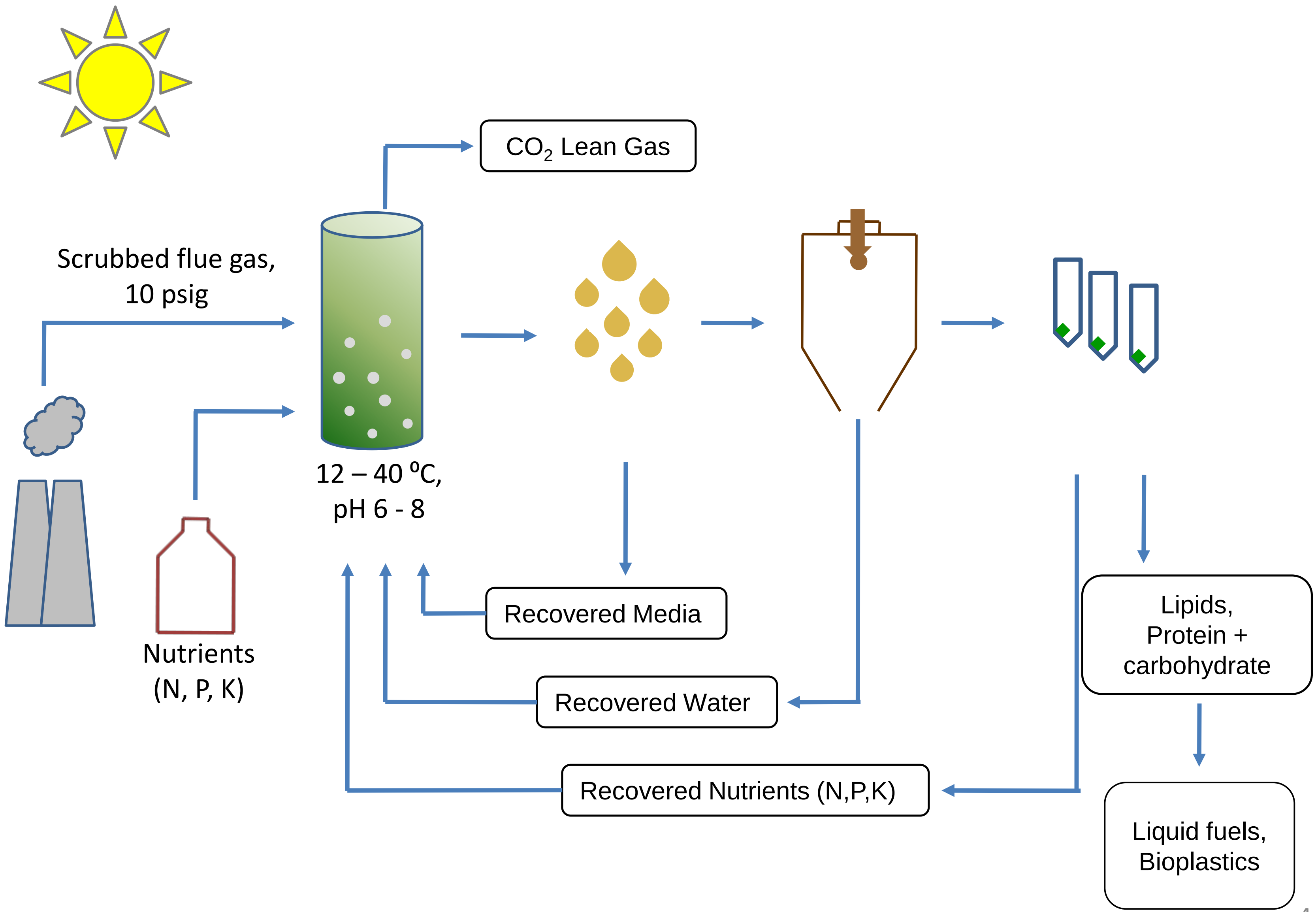
- A high-value biomass utilization strategy will be developed to simultaneously produce a lipid feedstock for the production of fuels, a carbohydrate feedstock for conversion to chemicals and/or bio-ethanol, and a protein-rich meal for the production of algal-based bioplastics

- Techno-economic analyses will be performed to calculate the cost of CO_2 capture and recycle using this approach, and a life cycle assessment will evaluate the potential for reducing greenhouse gas emissions.

Background:

Highlights from DE-FE0026396:
A Microalgae-based Platform for the Beneficial Reuse of CO_2 Emissions from Power Plants

Technology Background: Process Schematic



East Bend Station Demonstration Facility

DUKE ENERGY®

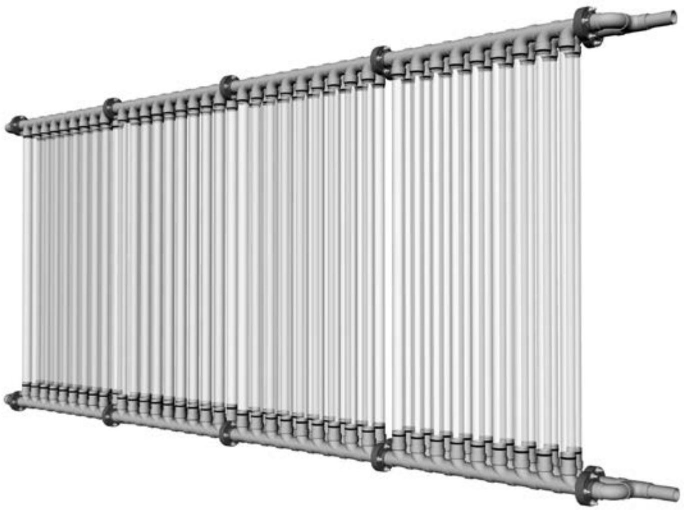
650 MW Scrubbed Unit (SCR, FGD, ESP)

<u>MAIN GOALS</u>

- 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

"Cyclic Flow" Photobioreactor (1100 L) Installed at East Bend (2nd Generation PBR)



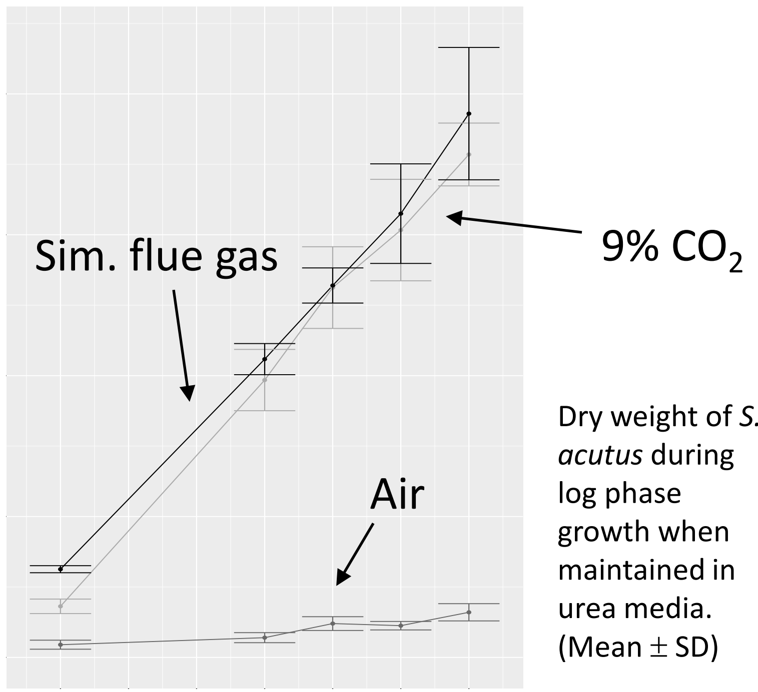
Summer 2014

May 2015

System Biology:
Effect of Flue Gas Constituents on Algae Growth

Experimental Design:

- Three gas treatments: Air/Control (400 ppm CO_2), 9% CO_2, and simulated flue gas (9% CO_2, 55 ppm NO, 25 ppm SO_2).
- Four replicate cultures for each treatment
- Flow rates were maintained between 2.3-2.5 ml/min for each replicate for all treatments.
- Cultures were acclimated to the gases for two batch cycles before starting experiment (transferred before reaching stationary phase)



Dry weight of *S. acutus* during log phase growth when maintained in urea media. (Mean ± SD)

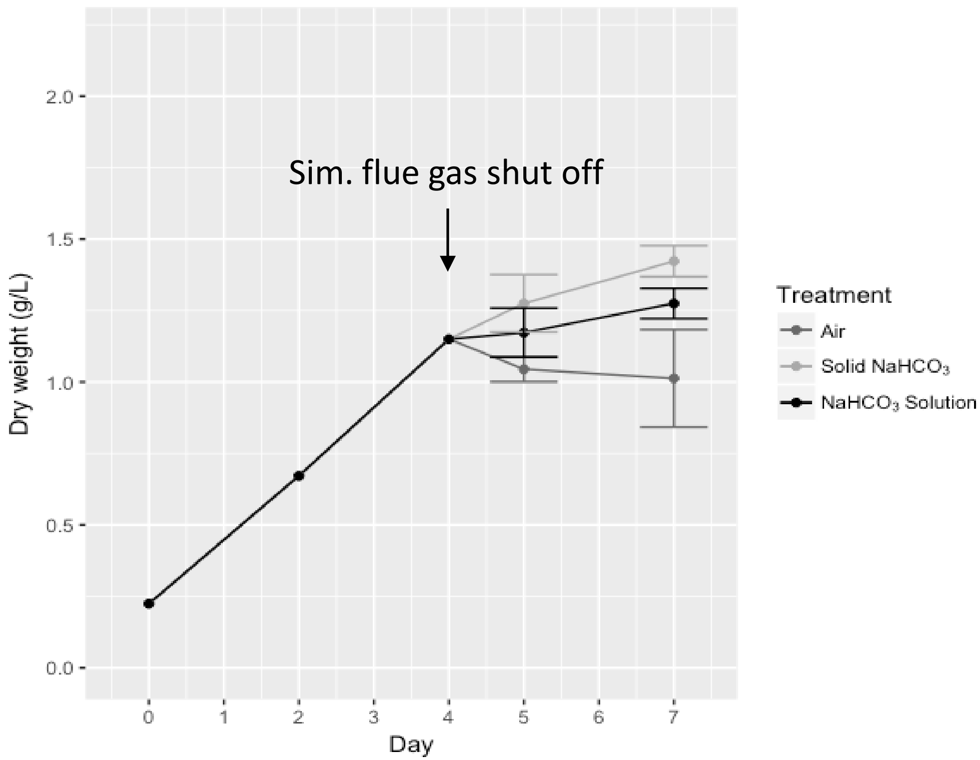
Results:

- There was no statistical difference in productivity between simulated flue gas and CO_2-grown cultures.

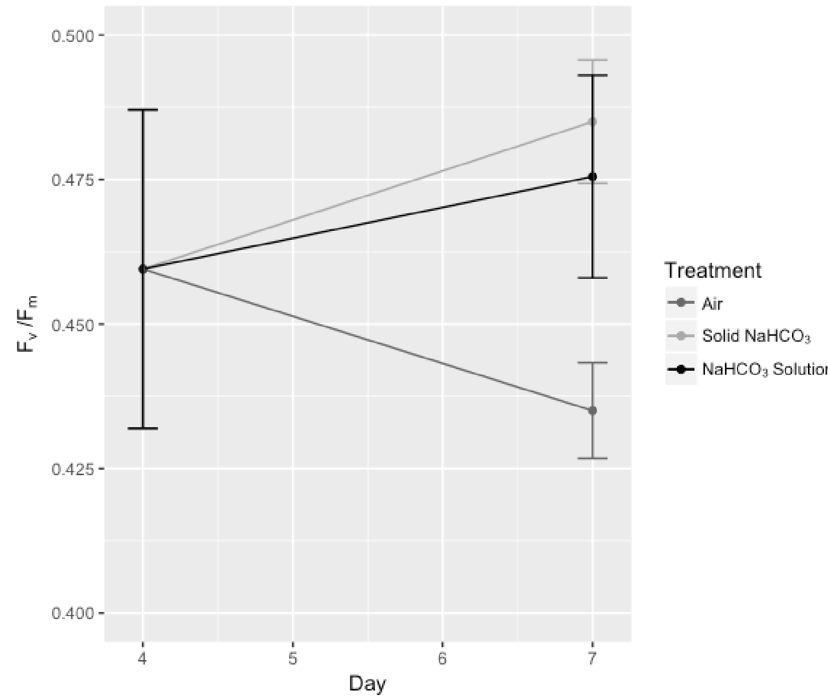
Productivity and specific growth rates during log phase growth when maintained in urea media

	Treatment		
	Air	CO_2	Flue Gas
Productivity (g L^{-1} Day^{-1})	0.018	0.268	0.266
Specific growth (μ)	0.22	0.389	0.307

System Biology:
Bicarbonate Addition as a Means of Sustaining Algae Cultures



Dry weight of *Scenedesmus acutus*. Arrow indicates where flue gas was shut off. (Mean ± SD)

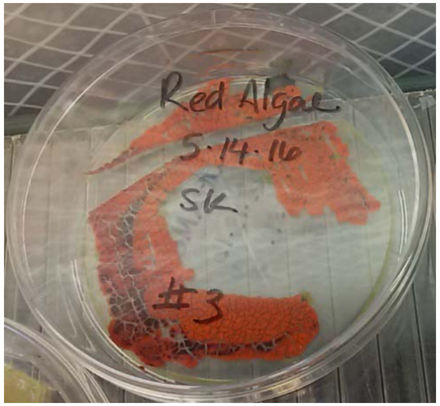


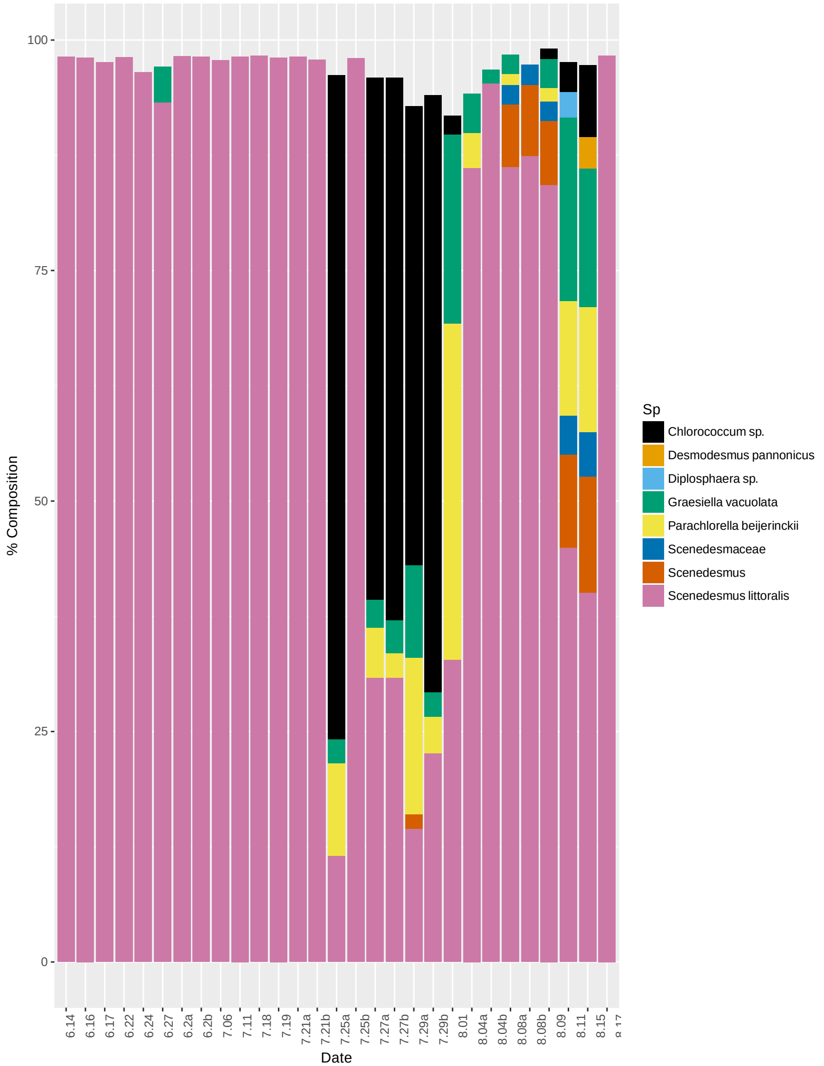
F_v/F_m (photosynthetic efficiency) for each treatment after flue gas was shut off. (Mean ± SD). F_v/F_m for the air treatment was significantly lower than for the other treatments

- $NaHCO_3$ addition (5 mM) shown to be effective for preserving culture health in absence of flue gas

System Biology: Analysis of East Bend PBR Algae Culture

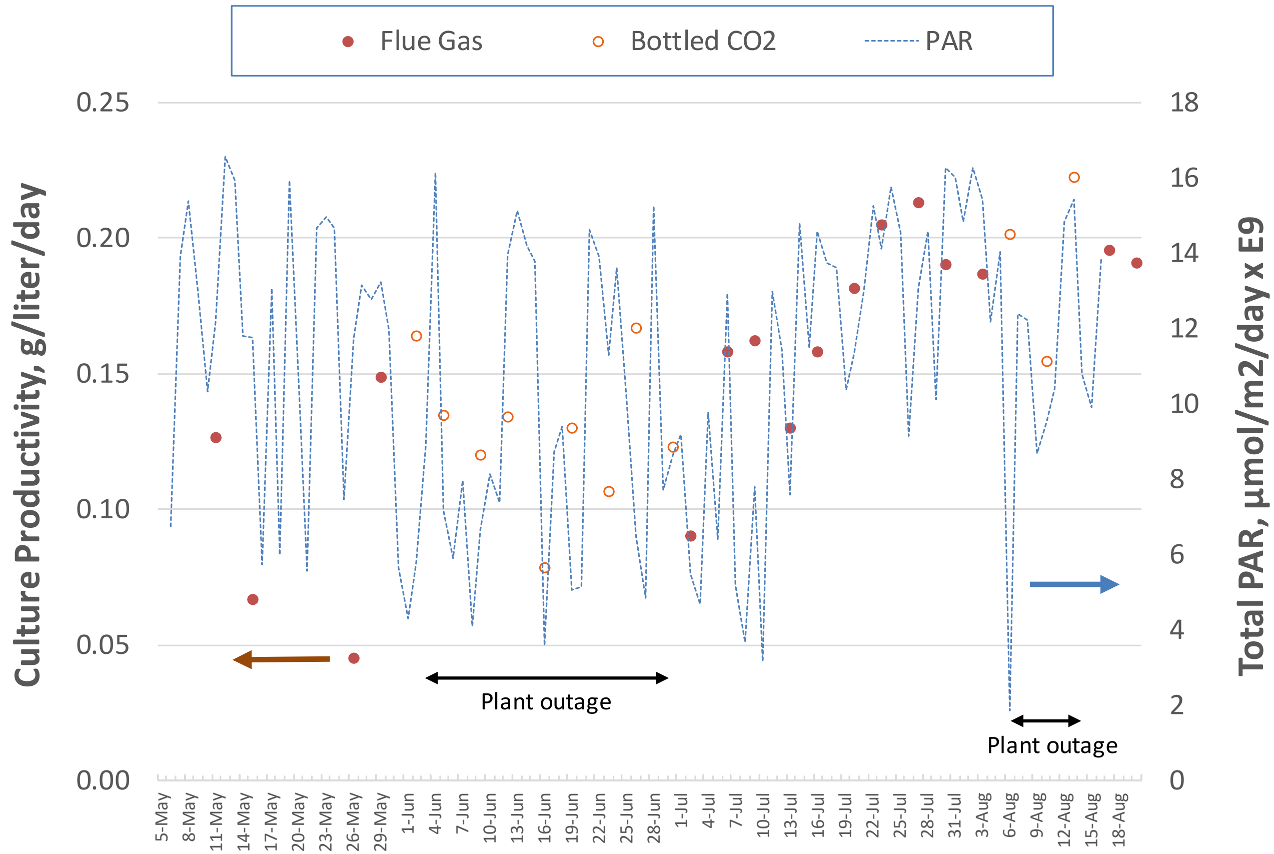
- Community sequencing analysis of the PBR in summer 2016 showed contamination by *Chlorococcum* sp. in mid to late July, followed by a contamination event that was dominated by *Graesiella vacuolata* and *Parachlorella beijerinckii*
- Towards the end of the culturing campaign at East Bend, excessive temperatures caused the *Scenedesmus* culture to crash. However, this provided an opportunity for an invasive species of algae to flourish, identified as *Coelastrella saipanesis*.
- Although a green alga, when stressed the cells turn red due to the production of a potentially valuable pigment (most likely β-carotene).





East Bend Algae Productivity

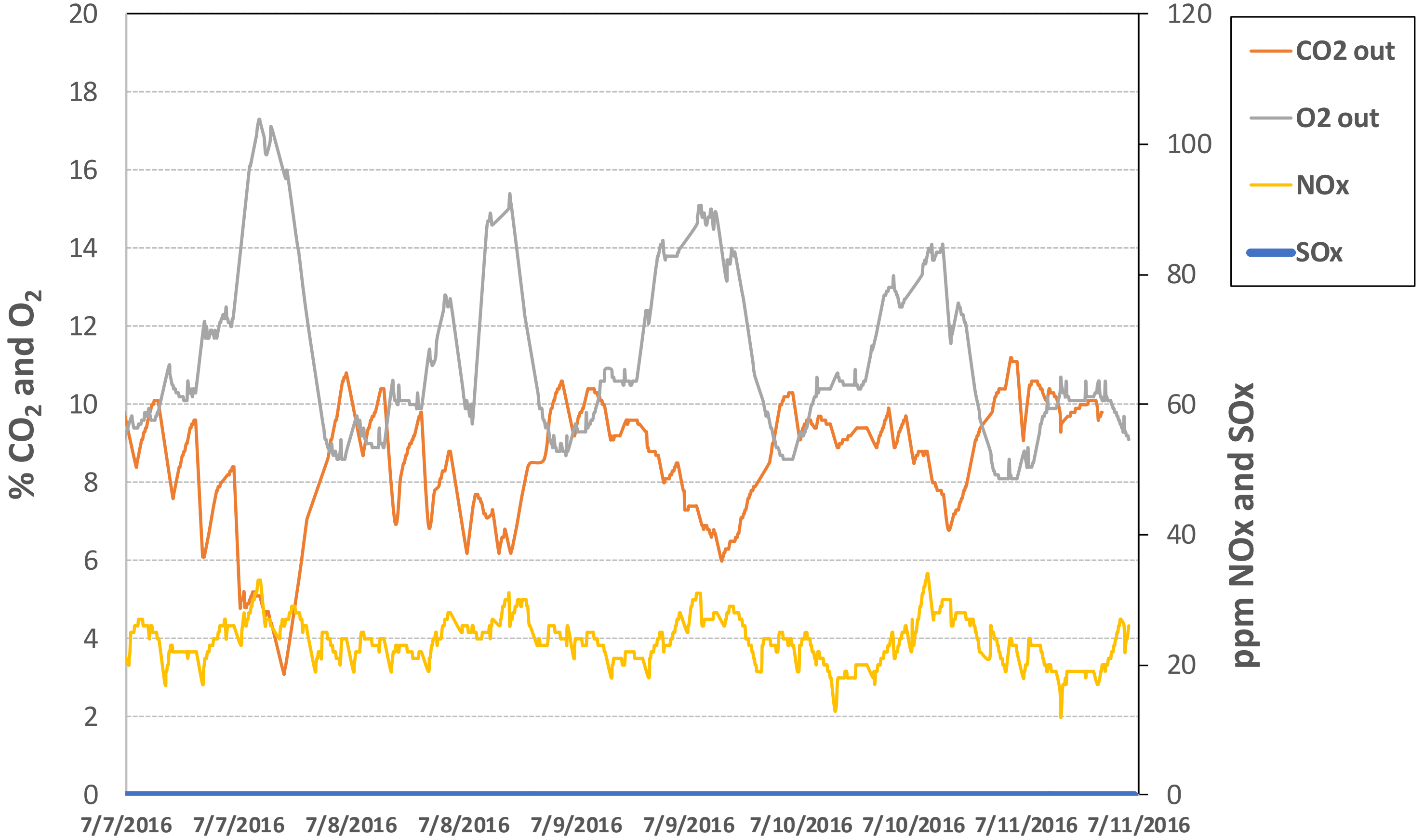
Summer 2015



- Algae productivity = 0.165 ± 0.057 g/(L.day), equivalent to ca. 35 g/(m^2.day)

M.H. Wilson, D.T. Mohler, J.G. Groppo, T. Grubbs, S. Kesner, E.M. Frazar, A. Shea, C. Crofcheck, M. Crocker, *Appl. Petrochem. Res.*, 2016, 6, 279-293.

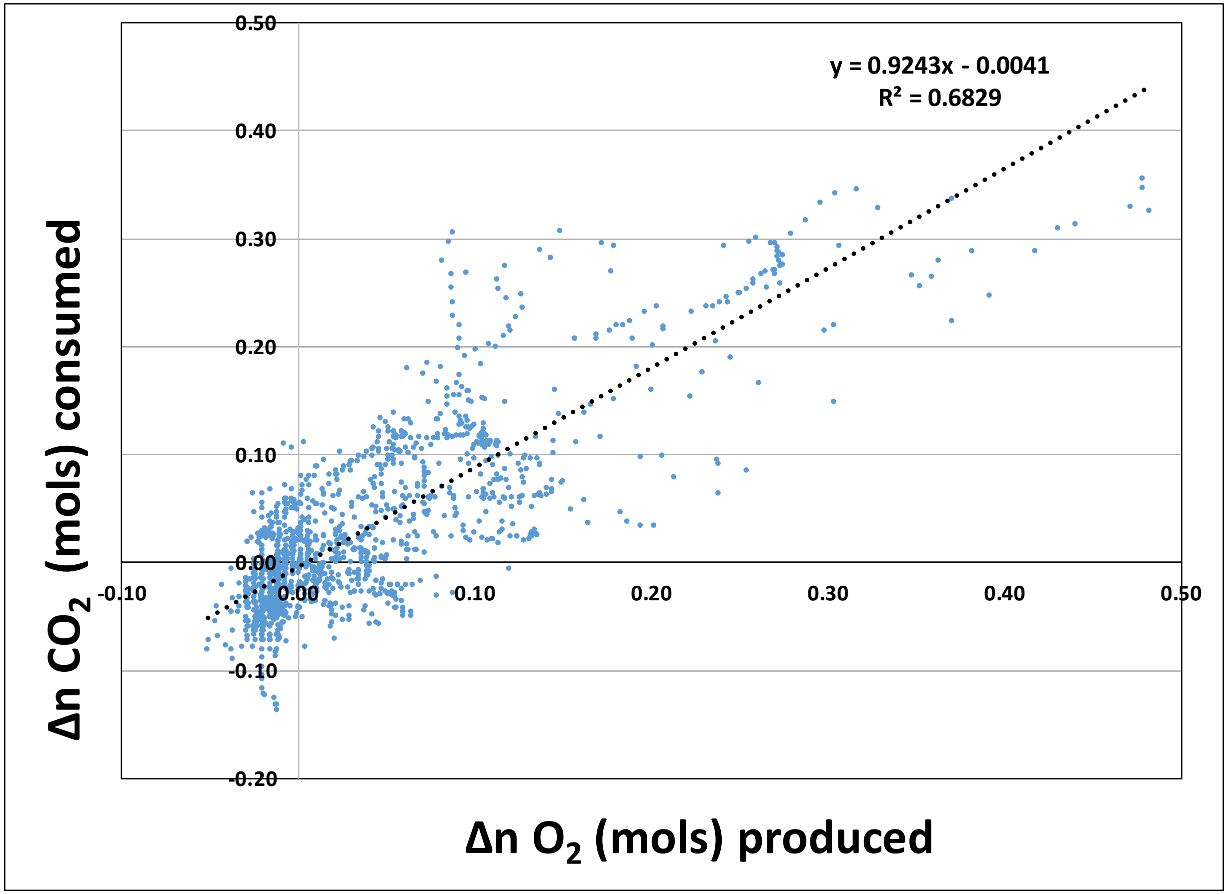
Typical PBR Outlet Gas Composition



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

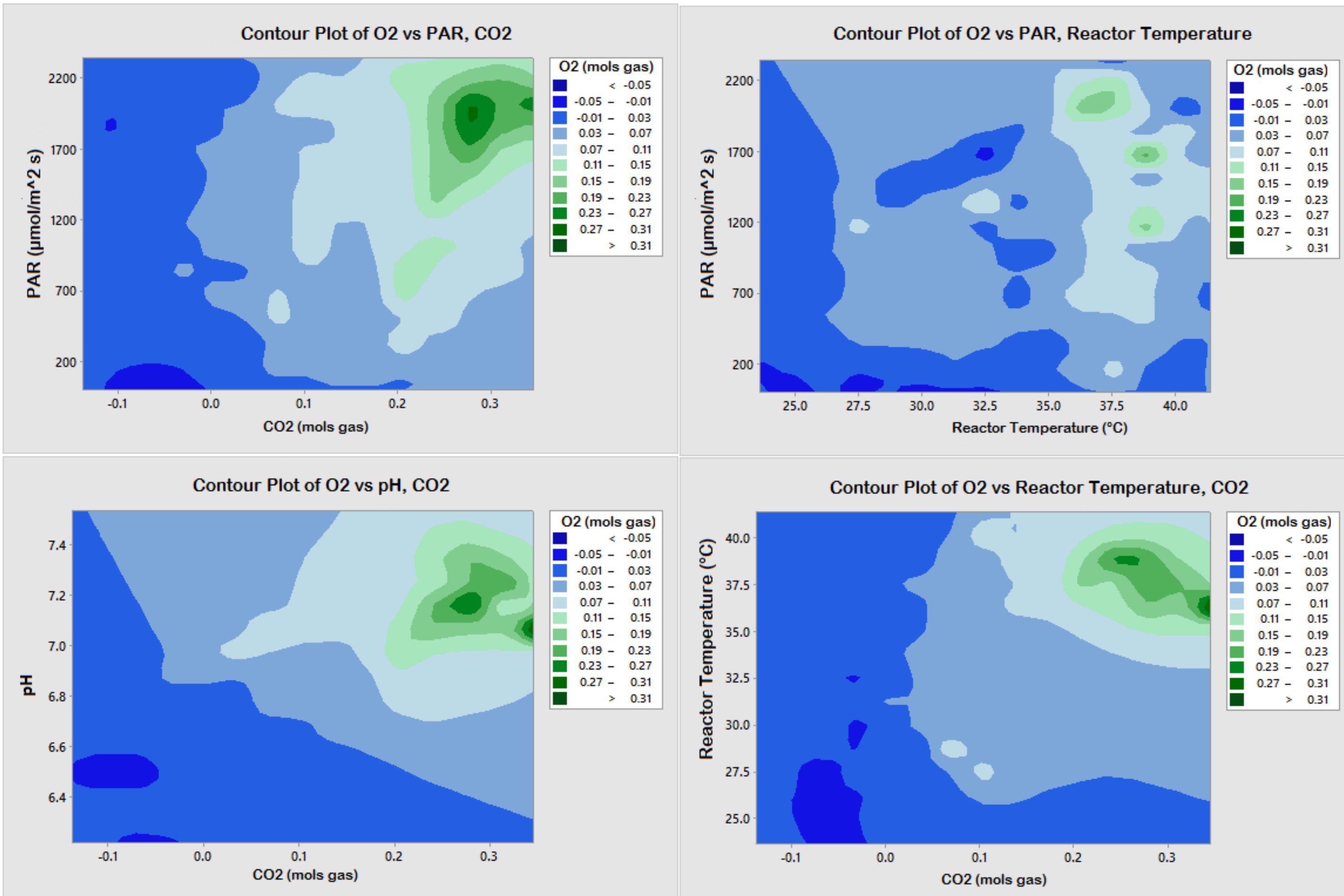
CO_2 Consumption vs. O_2 Production

CO_2 consumed vs. O_2 produced (5 s data). Graph indicates a direct linear correlation between CO_2 consumed and O_2 produced with a slope of 0.92 and intercept of 0.0041. The quality of the R^2 value was impaired by the inclusion of data corresponding to an unhealthy culture on 7/23/16.



- Data plot confirms close to linear relationship between CO_2 uptake and O_2 production, confirming that the latter is a good indicator of CO_2 consumption
- Observed O_2/CO_2 ratio of slightly greater than 1 (1.08 in this case) is consistent with literature

Engineering Analysis: East Bend Station Data (1200 L PBR)
O_2 Production vs. Process Temperature, PAR & pH



- Optimal O_2 production is more temperature dependent than previously thought
- Highest O_2 production trend occurs at process temperatures and PAR values of 35-38.5 ^{o}C and 1200-2000 μmol/(m^2s), respectively

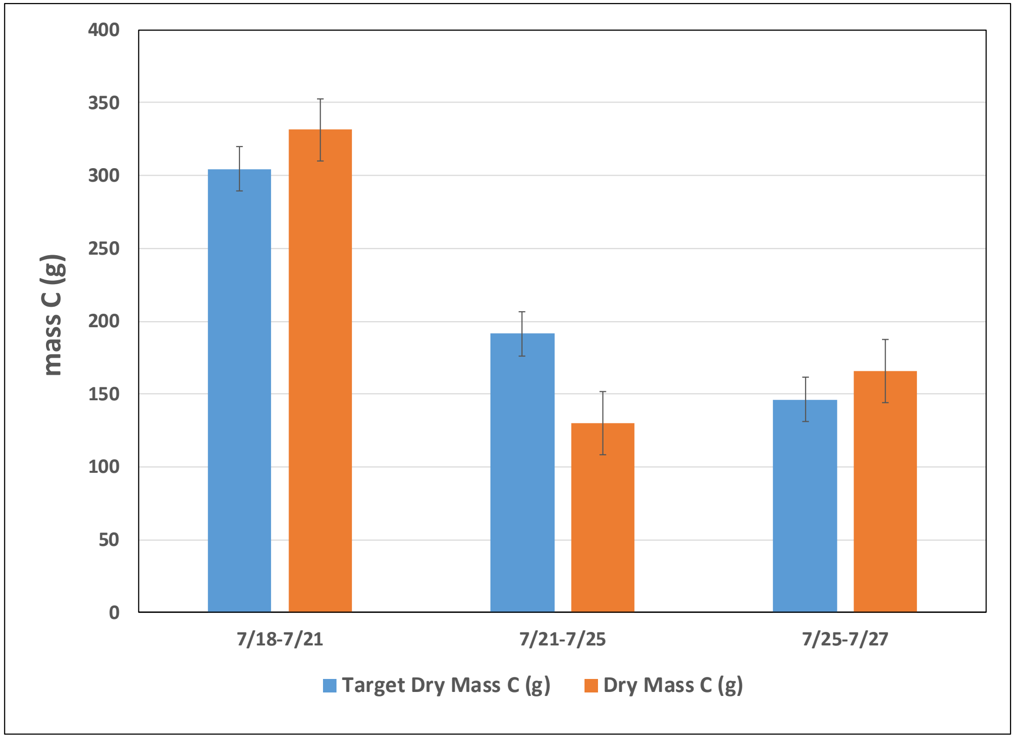
Carbon Mass Balance

(East Bend PBR, summer 2016)

$$m_{c_{dry\,mass}} = (\rho_2 - \rho_1)V_R w_c$$

$$m_{C_{target}} = m_{C_{gas}} + m_{C_{urea\,consumption}} - m_{C_{soln}}$$

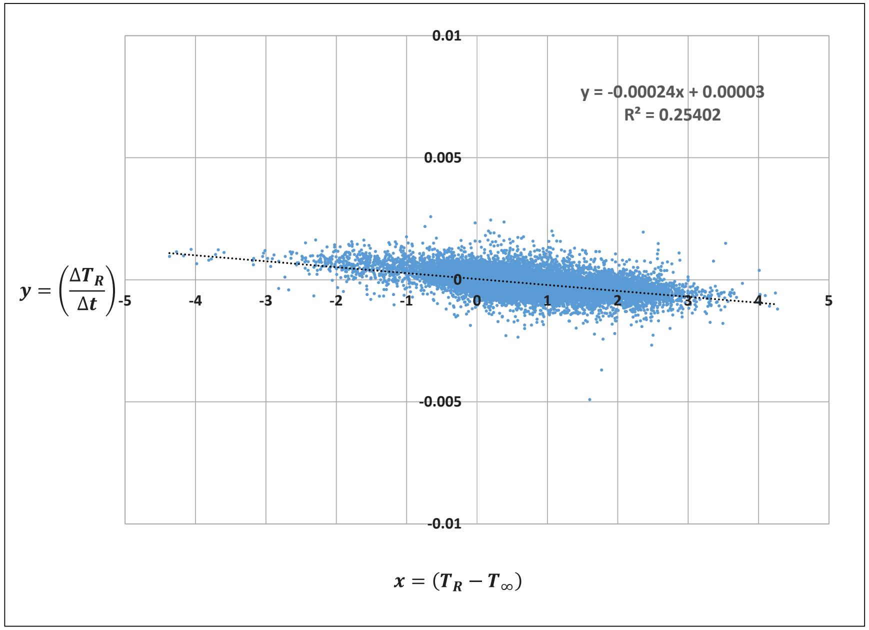
- Overall, reasonable agreement is obtained between measured carbon accumulation ("dry mass") and calculated carbon uptake in PBR ("target dry mass")
- The discrepancy in numbers for the 7/21-7/25 growth period can be attributed to significant biofilm formation within the reactor, as observed during that time.



Error bars represent the st. dev. for triplicate dry mass measurements (orange columns) and the error associated with the CO_2 gas analyzer (blue columns)

Analysis of Waste Heat Integration with PBR

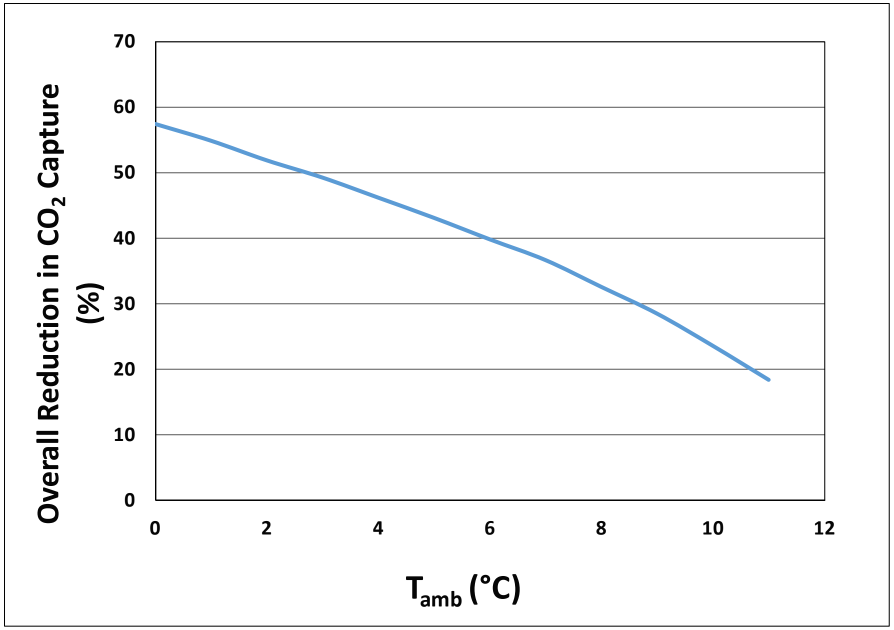
Experimental Determination of U (Overall Heat Transfer Coefficient) using Data from 2015 Growing Season



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

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

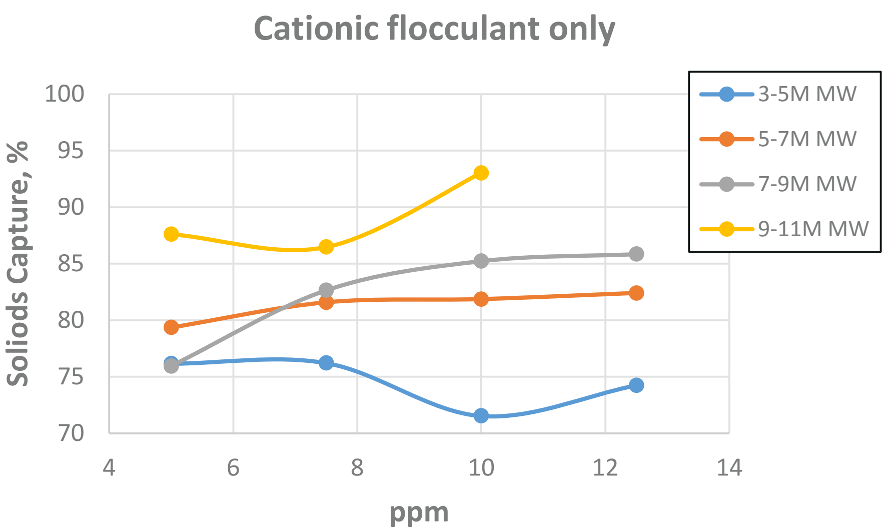
Reduction in Overall CO_2 Capture vs. Ambient Temperature



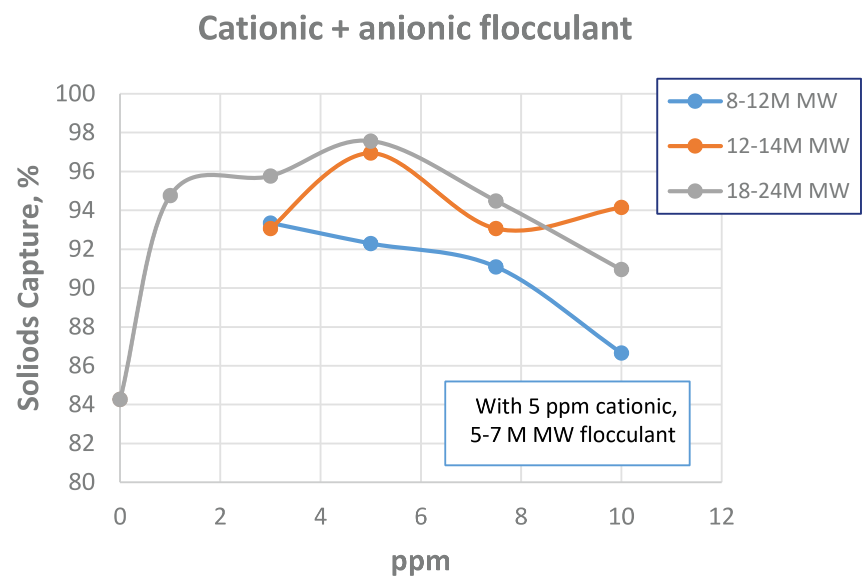
- Assumptions: 30% CO_2 capture from a 1 MW coal-fired power plant
- Heat source = boiler water (910,000 L/min, T = 32-45 ºC)
- Increased CO_2 emissions arise from pumping boiler water to PBR heat exchanger and increased cycling of PBR culture through heat exchanger

Biomass Harvesting:
Optimization of Flocculation Procedure

(Residence Time = 10 Min)



Effect of cationic flocculant dosage and molecular weight on solids capture of harvested algae (0.456 g/L)



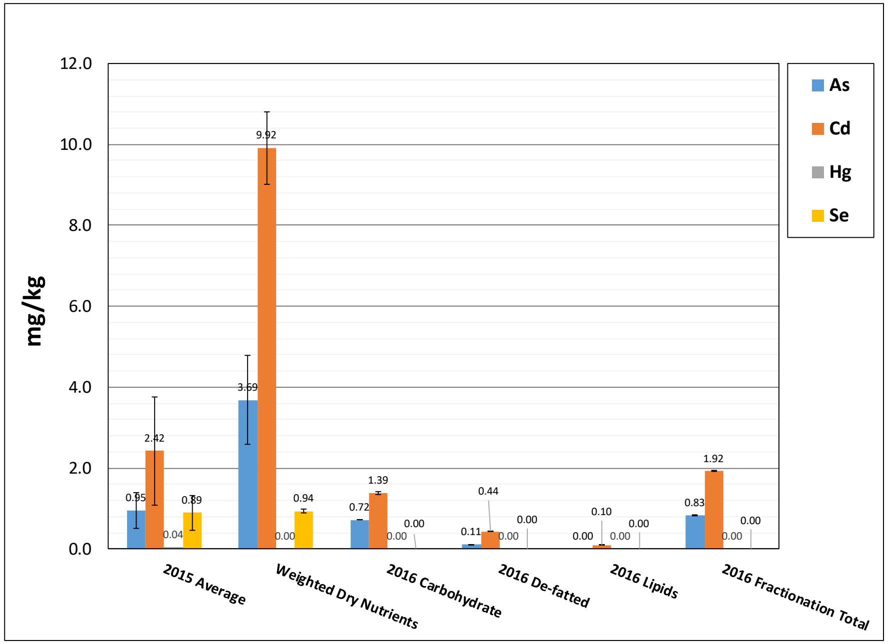
Effect of anionic flocculant dosage and molecular weight on solids capture of harvested algae pretreated with 5 ppm cationic flocculant

- Extent of solids capture is limited if only cationic flocculant is used (regardless of flocculant mol. wt.)

- Anionic flocculants by themselves are not effective
- However, 95% solids capture is possible by addition of 1 ppm of anionic flocculant to algae pre-flocculated with 5 ppm cationic flocculant

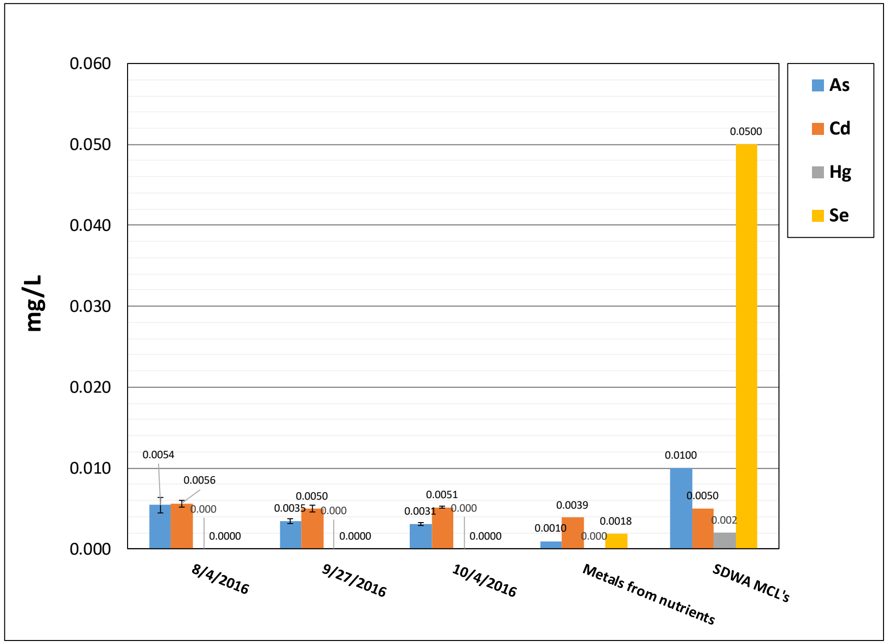
Heavy Metals Analysis

Analysis of solids



- 2015 averages are average of five samples of dry algae grown on flue gas at East Bend Station in 2015
- Weighted Dry Nutrients numbers represent the sum of all metals present in dry nutrients, weighted to reflect the nutrient mixture as it is added to the PBR

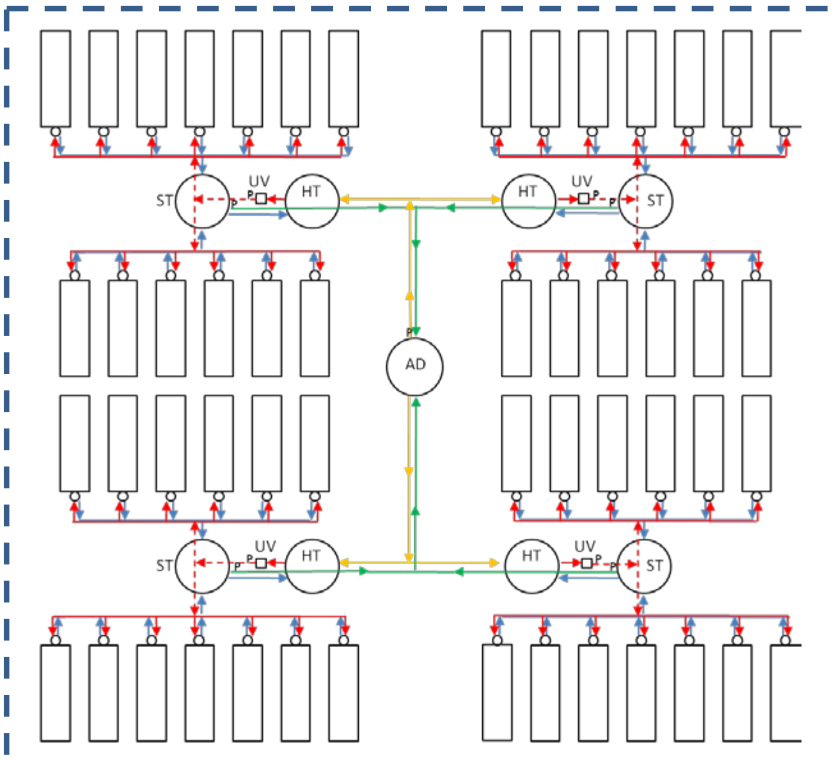
Analysis of nutrient broth in PBR



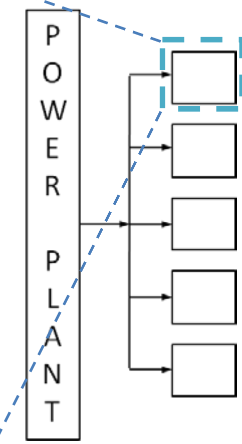
- “Metals from Nutrients” represents weighted calculation based on metals in dry nutrients and their respective target concentrations in algae media
- SDWA MCL’s represent the Maximum Contaminant Levels (MCL’s) for drinking water as regulated by the Safe Drinking Water Act of 1974

- Very low heavy metal concentrations detected in harvested algae – levels are consistent with heavy metals incorporation from supplied nutrients

Life Cycle Assessment



Schematic of a section of the algae system consisting of 52 PBR modules, 4 settling tanks (ST), holding tanks (HT), and UV sterilizers (UV).



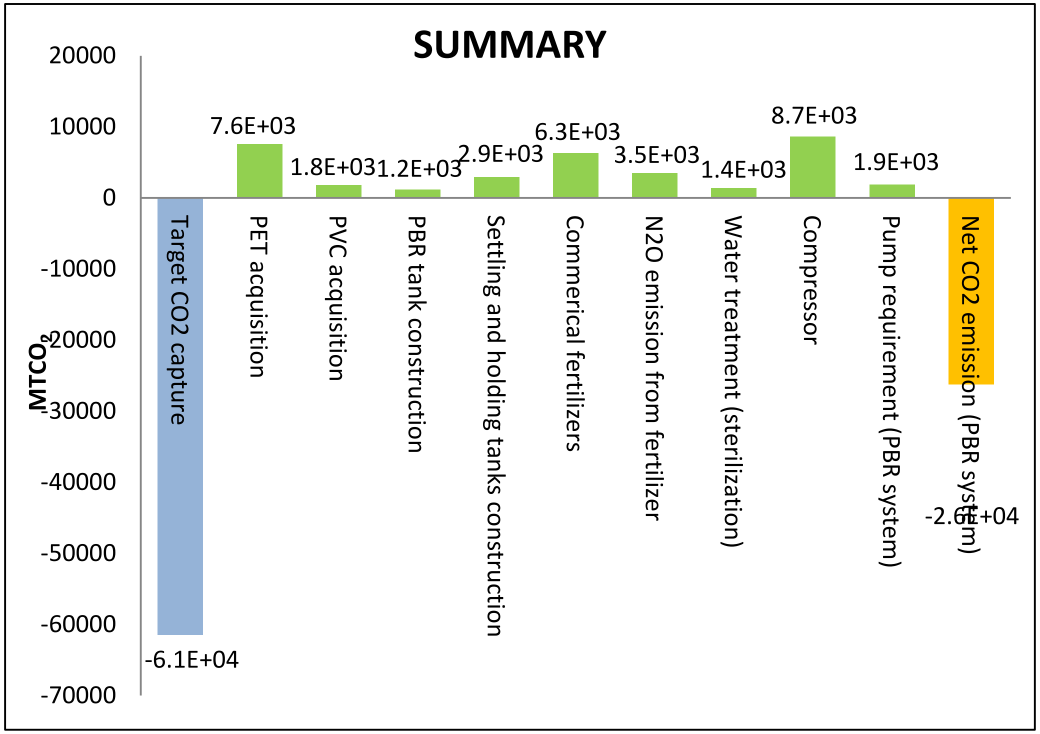
A schematic of the algae system (260 PBR modules; 260 individual feed tanks, feed pumps, and compressors; 20 individual settling tanks, holding tanks, and UV sterilizers)

- A life cycle assessment (LCA) was developed for an algae system based on UK's cyclic flow PBR, **mitigating 30% of the CO_2 emitted by a 1 MW coal-fired power plant**.
- Operation of the algae system included cumulative process requirements and energy consumption associated with algae cultivation, harvesting, dewatering, nutrient recycling, and water treatment.

Life Cycle Assessment: Results

- CO_2 emission associated with the gas compressor was 8.7 x 10^3 metric tons, due to the large amount of flue gas (4422 m^3/h) being compressed at full capacity for 12 h per day.
- PBR feed pumps emitted a lesser amount of CO_2 (1.9 x 10^3 metric tons) on account of the cyclic flow operation mode.
- The PBR system was able to capture 43% (2.6 x 10^4 metric tons) of the target CO_2 emission (6.1 x 10^4 metric tons).
- The LCA results demonstrate that a PBR algae system can be considered as a CO_2 capture technology.

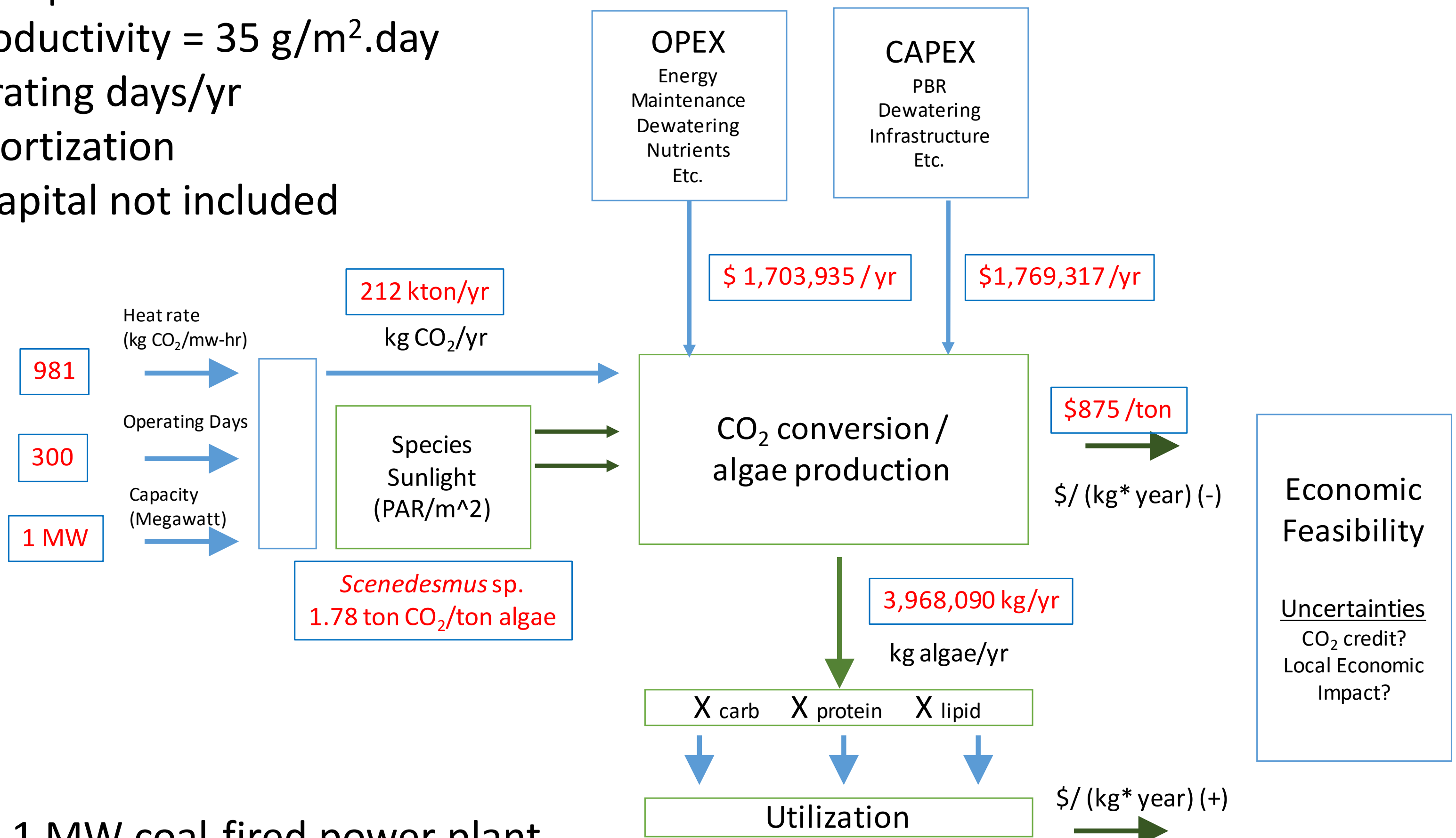
POWER PLANT		
Capacity	1	MW
CO_2 emission	22.76	ton/day
CO_2 capture	30	%
CO_2 emission mitigated	6.83	ton/day
Operation	300	day/year
ALGAE		
Strain	*Scenedesmus acutus*	
Growth rate	0.15	g/L/day
Culture density at harvest	0.8	g/L (dry weight)
Algae required for 30% CO_2 capture	3.88	ton/day



Techno-economic Analysis

US Scenario (best case):

- 30% CO_2 capture
- Algae productivity = 35 g/m^2.day
- 300 operating days/yr
- 30 yr amortization
- Cost of capital not included

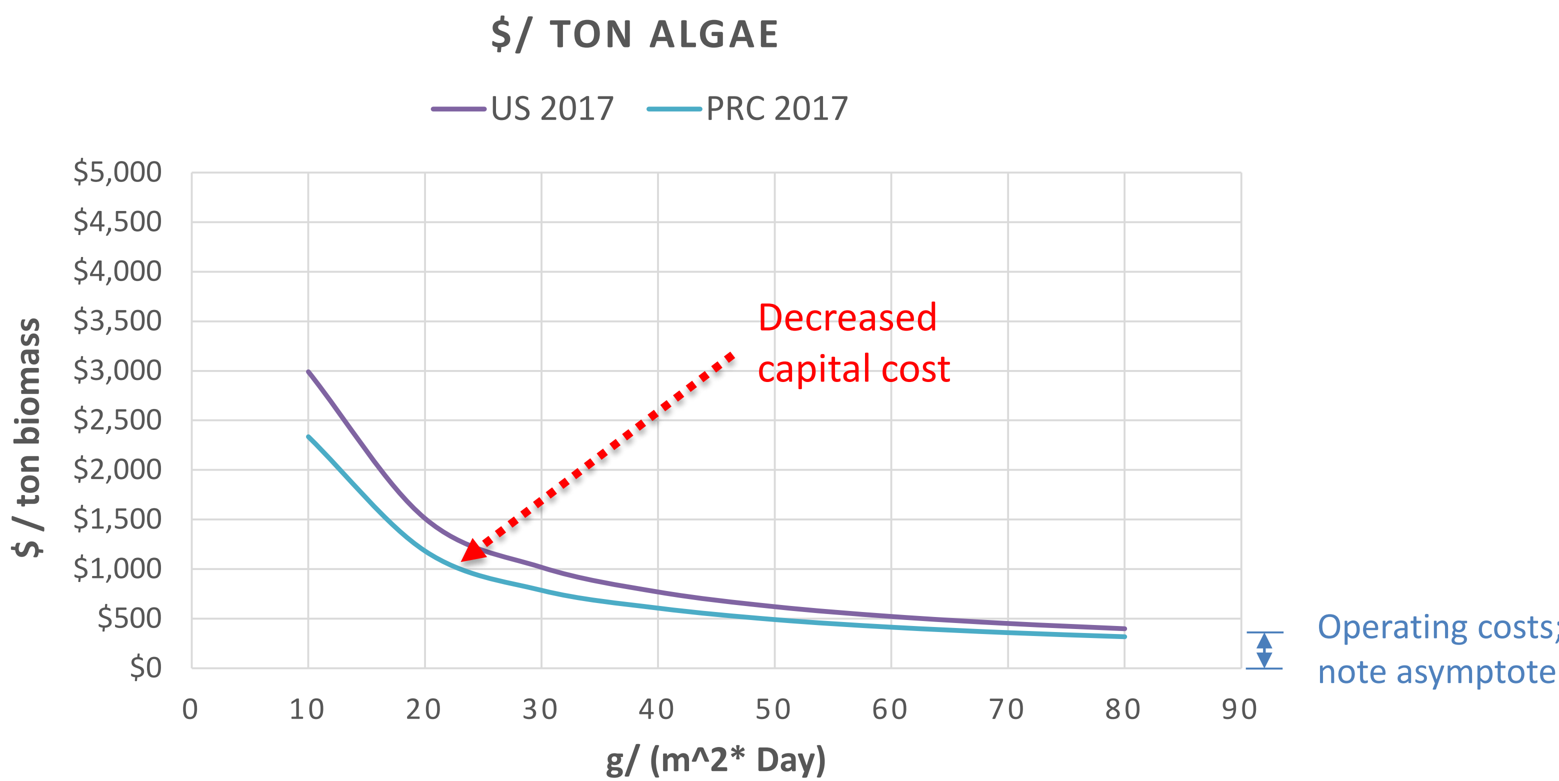


Base case: 1 MW coal-fired power plant

Estimated min. algae production cost = **$875/ton**

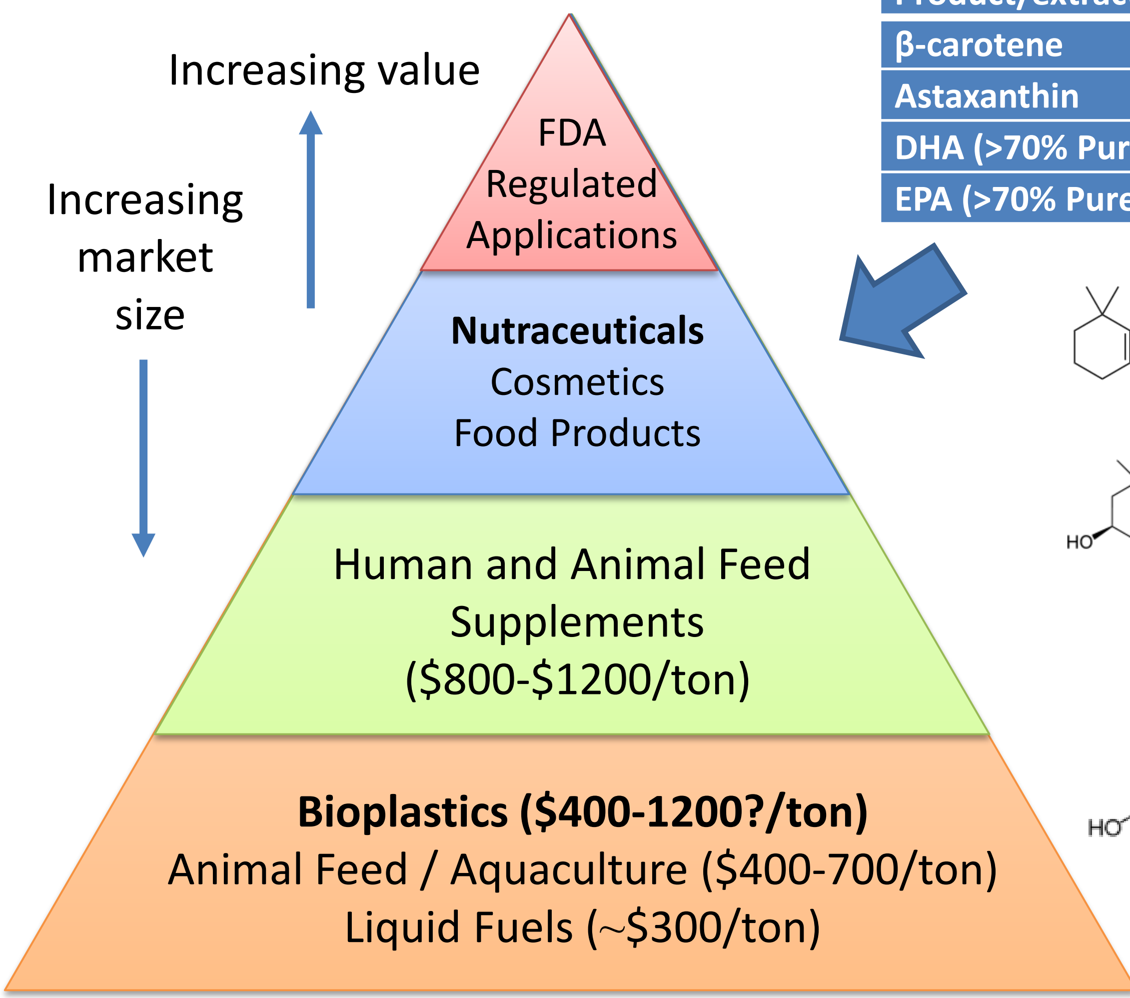
(biomass dewatered to 10-15 wt% solids)

Techno-economic Analysis (cont.)

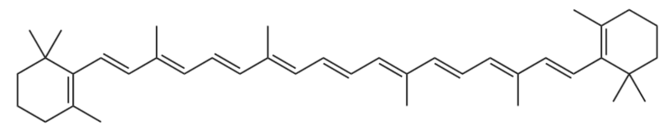


- Cost estimates (2017) are consistent with projections from prior analysis (2013), showing considerable progress toward economic viability
- Asymptote relates to operating costs

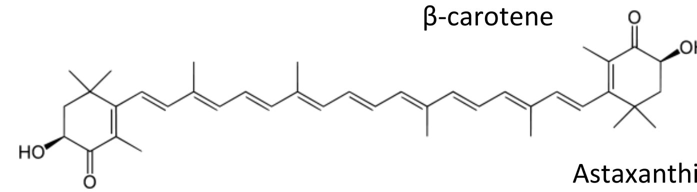
Algal Biomass Utilization



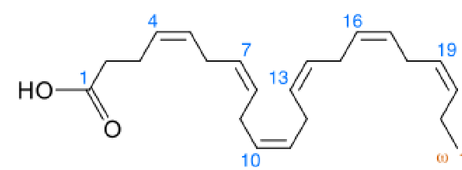
Product/extract	Selling price	Wt% in algae
β-carotene	\$300-3000/kg	14%
Astaxanthin	\$2500-7150/kg	3%
DHA (>70% Pure)	~\$12,540/kg	7.8%
EPA (>70% Pure)	~\$12,540/kg	4%



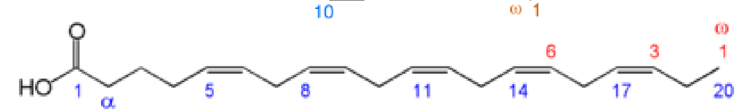
β-carotene



Astaxanthin



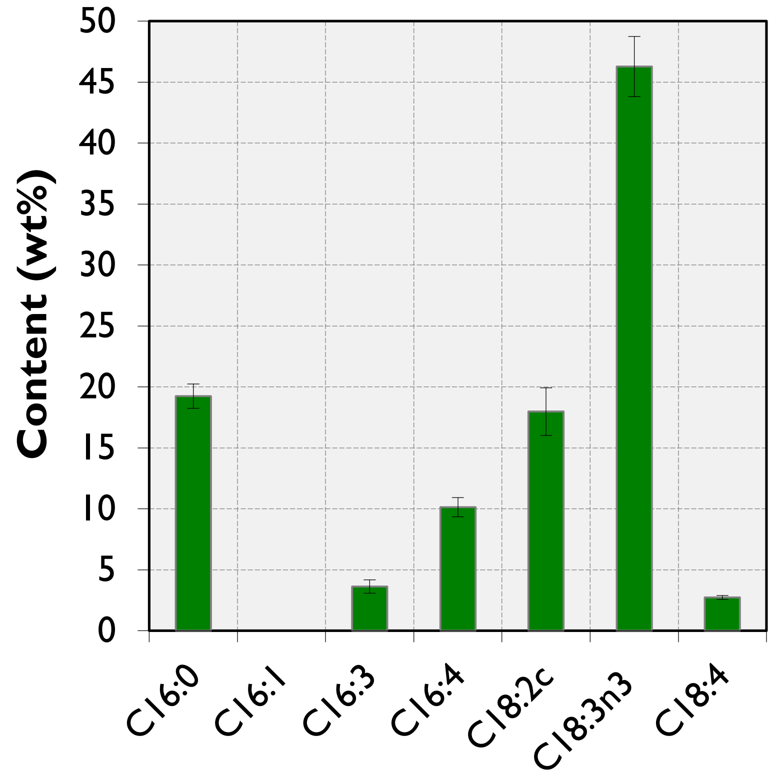
DHA



EPA

Lipid Extraction and Characterization

- Wet *Scenedesmus*, typically ~15 wt% solids
- Ultrasound, microwave irradiation and bead beating all proved ineffective for cell lysing
- Acidification to pH 1-2 using aq. HCl/MeOH results in cell lysing and simultaneous lipid (trans)esterification*
- Yield of esterifiable lipids = 6.3 (+/- 0.1) wt%, close to value reported previously for dry *Scenedesmus***
- Lipids from this strain of *Scenedesmus acutus* are highly unsaturated: ALA (α-linolenic acid) accounts for almost 50% of total lipids

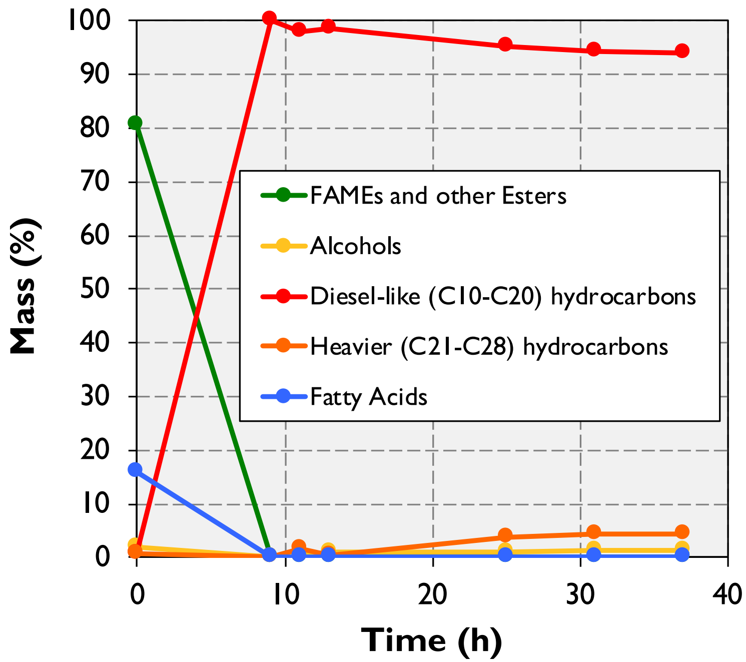


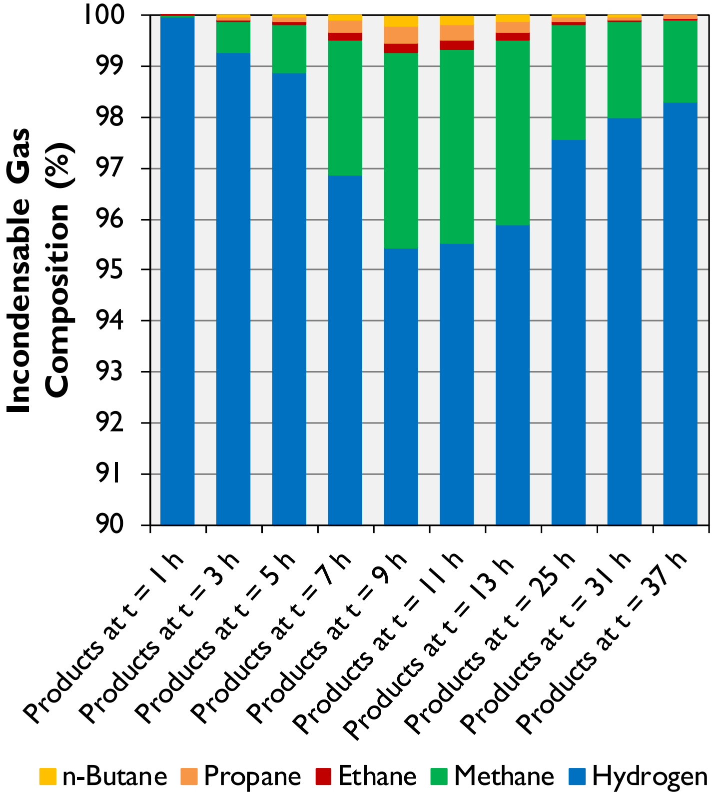
* L.M.L. Laurens, M. Quinn, S. Van Wychen, D.W. Templeton, E.J. Wolfrum, *Anal. Bioanal. Chem.*, 403 (2012) 167-178.
**E. Santillan-Jimenez, R. Pace, S. Marques, T. Morgan, C. McKelphin, J. Mobley, M. Crocker, *Fuel* 180 (2016) 668-678.

Upgrading of Extracted Algal FAMES to Hydrocarbons

75 wt% algal FAMEs in dodecane, WHSV = 1 h^{-1}, Temp. = 375 °C

20% Ni – 5% Cu/Al_2O_3 catalyst





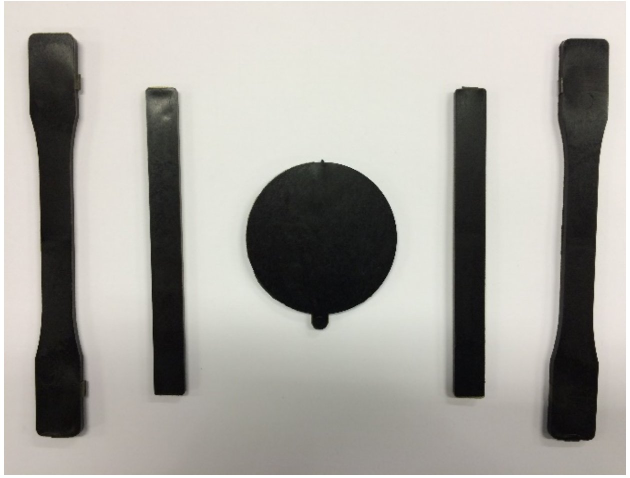
- >90% liquid products are diesel-like hydrocarbons at all reaction times
- Methane yield decreases after induction period, indicating poisoning of cracking sites

E. Santillan-Jimenez, R. Loe, M. Garrett, T. Morgan, M. Crocker, *Catal. Today*, 2017, http://dx.doi.org/10.1016/j.cattod.2017.03.025.

Composition of Whole and Defatted Algae

Sample	Ash (wt%)	Protein (wt%)	Volatiles (GC/MS)
Whole	11.1	44.2	16 peaks at 140 °C; 196 peaks at 200 °C
Defatted	15.6	50.7	12 peaks at 140 °C; 121 peaks at 200 °C

- Increase in protein and ash content consistent with removal of lipids
- Fewer compounds were released upon heating to 200 °C for the defatted algae, suggesting that lipid extraction may have improved thermal stability
- Defatted algal biomass has improved odor properties
- Defatted algae used for production of maleic anhydride compatibilized EVA (ethylene vinyl acetate) composite, containing 30 wt% algae



EVA composite test parts

Summary (DE-FE0026396)

- Very low heavy metal concentrations detected in harvested algae – levels are consistent with heavy metals incorporation from supplied nutrients
- An improved protocol for algae harvesting was developed, based on the use of cationic + anionic flocculants
- LCA showed that the cyclic flow PBR qualifies as a net CO_2 capture technology
- TEA indicates a best case scenario production cost of $875/ton for *Scenedesmus acutus* biomass
- A procedure was developed for lipid extraction from wet *Scenedesmus* biomass
- Extracted lipids were upgraded to diesel-range hydrocarbons
- Defatted biomass possessed improved odor properties for bioplastic applications

DE-FE0029632:
Technical Approach/Project Scope

Key Issues to be Resolved

1) Can algal biomass production costs be lowered by the use of a combined PBR + pond cultivation system?

   → Combine the low capex of ponds with the high productivity of PBRs

   → Comparison of pond, PBR, and PBR/pond systems (TEA and LCA)

2) In the case of algae-based bioplastic production, which processing scheme offers the greatest potential for revenue generation and large-scale application?

   → Whole biomass vs. wet lipid extraction vs. combined algal processing (CAP)

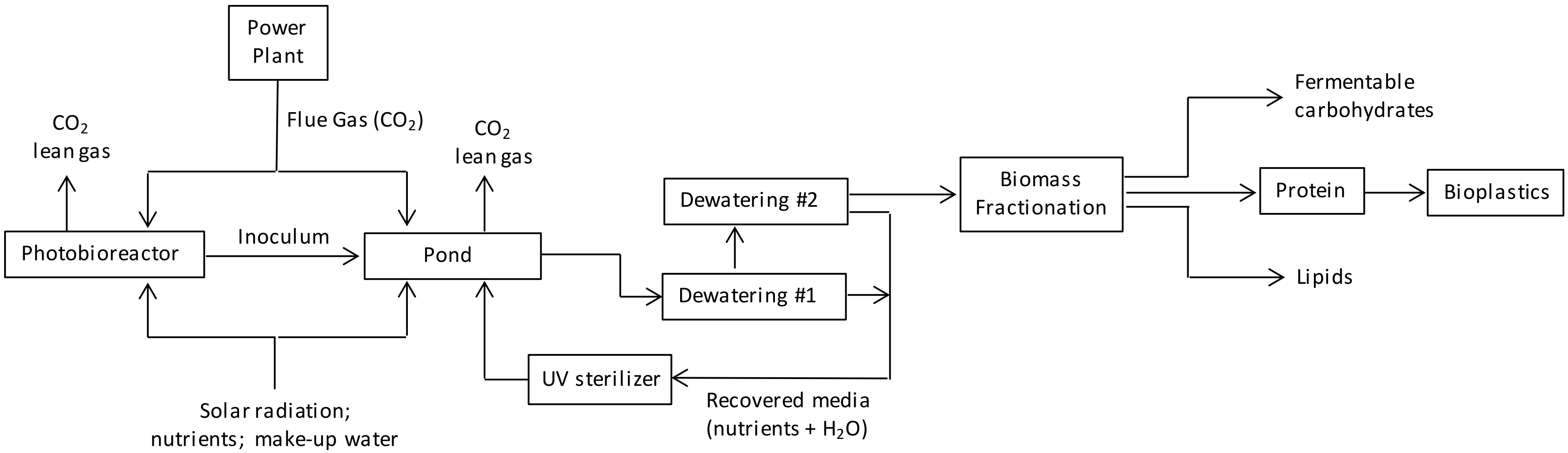
3) From a TEA and LCA perspective, which cultivation system and processing scheme(s) offer the greatest potential?

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 for conventional systems (<50%)
- Challenging economics: cost of algae cultivation is high (currently >$1,000/MT), hence require high value applications for produced algae biomass
- Market size generally inversely related to application value (hence risk of market saturation)

Technical Approach/Project Scope



Year 1:

- Task 1: Project Management
- Task 2: LCA and TEA
  - develop engineering process model for ponds, PBR and PBR/pond hybrid system
- Task 3: Algae Cultivation
  - pond and PBR installation
  - pond operation: comparison of pond and PBR/pond hybrid system productivity
  - monitor hydrolysate quality and composition for pond and PBR/pond cultures
- Task 4: Biomass Processing
  - wet lipid extraction with carbohydrate recovery
  - combined algal processing evaluation
  - bioplastic compounding

Technical Approach/Project Scope (cont.)

Year 2:

- Task 5: LCA and TEA II
  - initial TEA
  - initial LCA

- Task 6: Algae Cultivation II: Demonstration
  - site preparation
  - PBR and pond operation
  - monitor culture health and identify potential contaminants

  Task 7: Biomass Processing II: Valorization and Scale-up
  - market analysis – sugars and lipids
  - bioplastic material characterization and film/fiber demonstration

Year 3:

- Task 8: LCA and TEA III: Refinement of Sustainability Modeling
  - PBR temperature and growth modeling
  - resource assessment
  - data incorporation
  - technology gap analysis

Project Partners

- **UK CAER (Prof. Mark Crocker):**
  - Project management
  - Operation of PBR/pond systems, data collection and analysis
  - Biomass fractionation (CAP and wet lipid extraction processes)

- **UK Horticulture (Prof. Seth Debolt):**
  - Analysis of extractable sugars from *Scenedesmus* cultures
  - Genetic monitoring of species abundance in *Scenedesmus* cultures

- **Colorado State University (Prof. Jason Quinn):**
  - Engineering model development
  - TEA
  - LCA

- **Algix LLC (Ashton Zeller):**
  - Biomass characterization
  - Bioplastic compounding
  - Characterization of molded test specimens

Project Timeline

				Budget period 1				Budget period 2				Budget period 3			
				6/1/17-5/31/18				6/1/18-5/31/19				6/1/19-5/31/20			
Tasks and Milestones	Start	End	Cost	Q 1	Q 2	Q 3	Q 4	Q 1	Q 2	Q 3	Q 4	Q 1	Q 2	Q 3	Q4
1.0 Project Management	6/1/2017	5/31/2020	$119,845												
1.1 Stakeholder Meetings															
1.2 Reporting	6/1/2017	5/31/2020													
Milestone 1: Project kick-off meeting															
2.0 LCA/TEA I	9/1/2017	2/28/2018	$76,166												
2.1 Engineering Process Modeling	9/1/2017	2/28/2018													
Milestone 2.1: Engineering system model completed															
3.0 Algae Cultivation I: Lab/Pilot Scale Investigation	6/1/2017	5/31/2018	$192,928												
3.1 Pond Installation	6/1/2017	8/31/2017													
3.2 PBR + Pond Operation	9/1/2017	2/28/2018													
3.3 Monitor Hydrolystate Quality and Composition	12/1/2017	5/31/2018													
Milestone 3.1: Pond and PBR/pond systems operational															
4.0 Biomass Processing I: Biorefinery Concept Development	6/1/2017	5/31/2018	$109,453												
4.1 Optimization of Wet Lipid Extraction	6/1/2017	11/30/2017													
4.2 Combined Algal Processing Evaluation	12/1/2017	5/31/2018													
4.3 Bioplastic Compounding	12/1/2017	5/31/2018													
Milestone 4.2: > 50% sugars & >80% lipids recovered															
5.0 LCA/TEA II	6/1/2018	5/31/2019	$149,341												
5.1 Initial Techno-economic Analysis	6/1/2018	11/30/2018													
5.2 Initial Life Cycle Assessment	12/1/2018	5/31/2019													
Milestone 5.2: Initial LCA showing net CO_2 capture															
6.0 Algae Cultivation II: Demonstration	6/1/2018	5/31/2019	$211,779												
6.1 Site Preparation	6/1/2018	8/31/2018													
6.2 PBR and Pond Operation	9/1/2018	2/28/2019													
6.3 Monitor Culture Health and Identify Contaminants	12/1/2018	5/31/2019													
Milestone 6.1: Ponds and PBR/ponds installed at East Bend															
7.0 Biomass Processing II: Valorization and Scale Up	6/1/2018	5/31/2019	$133,244												
7.1 Market Analysis (sugars & lipids)	6/1/2018	11/30/2018													
7.2 Bio-Plastic Material Characterization	12/1/2018	5/31/2019													
Milestone 7.2: Bioplastic fiber vs film comparison															
8.0 LCA/TEA III	6/1/2019	5/31/2020	$264,037												
8.1 PBR Temperature and Growth Modeling	6/1/2019	11/30/2019													
8.2 Resource Assessment	12/1/2019	5/31/2020													
8.3 Data Incorporation	9/1/2019	2/28/2020													
8.4 Technology Gap Analysis	3/1/2020	5/31/2020													
Milestone 8.3: CO_2 capture cost & revenue stream quantified															
Milestone 8.4: Technology gap analysis complete															

Key Milestones – Year 1

Task	Description	Planned completion date	Status
Task 1: Project Management	Kickoff meeting	6/30/2017	Completed: 8/8/2017
Task 3: Algae Cultivation	Ponds installed at UK CAER	8/31/2017	Completed: 9/7/2017
Task 2: LCA and TEA	Engineering process model developed	5/31/2018	No change
Task 4: Biomass Processing	>80% lipids & >50% fermentable sugars recovered from algae	5/31/2018	No change

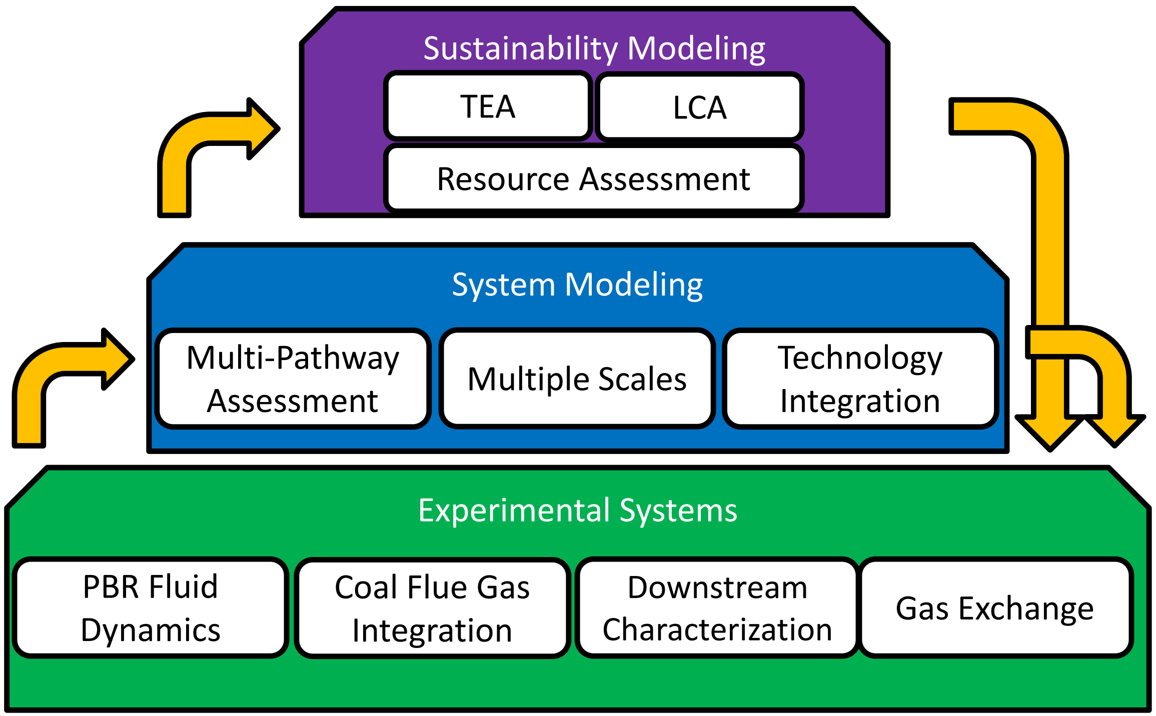
Success Criteria

Decision Point	Date	Success Criteria
Algae productivity	5/31/2018	PBR/pond cultivation system demonstrated to show superior productivity to pond-only system
Fractionation of algal biomass	5/31/2019	(i) 10 lb of algae produced for utilization studies (ii) >80% lipids and >50% fermentable sugars recovered from algae
Validation of bioplastic properties	5/31/2019	At least one bioplastic formulated with defatted algae identified to be commercially viable based on material properties
Algae productivity	5/31/2019	>15 g/m^2 algae production demonstrated for hybrid cultivation system using coal-derived flue gas
Life cycle assessment	5/31/2019	Life cycle assessment shows net positive greenhouse gas emission reduction
Techno-economic analysis	5/31/2020	Economic viability of proposed process demonstrated

Technical Risks and Mitigation Strategies

Description of Risk	Probability	Impact	Risk Management Mitigation and Response Strategies
Pond crashes due to contamination by rotifers or algal viruses	Moderate	High	Ponds to be sterilized after culture crash; continuous operation of PBR will allow for immediate pond re-seeding
Culture contamination due to invasive species in pond	High	Moderate	By maintaining high *Scenedesmus* culture density (by means of PBR "overseeding" strategy), major contamination will be minimized
Inclement weather (heat wave)	Low	High	Switch to warm weather algae strain
Algae meal from CAP unsuitable for bioplastics	Moderate	Moderate	Use algae meal obtained from wet lipid extraction
LCA shows process to be net CO_2 positive	Low	High	Use results to inform process development (avoid processing steps with high CO_2 emissions)

Task 2: Sustainability Modeling



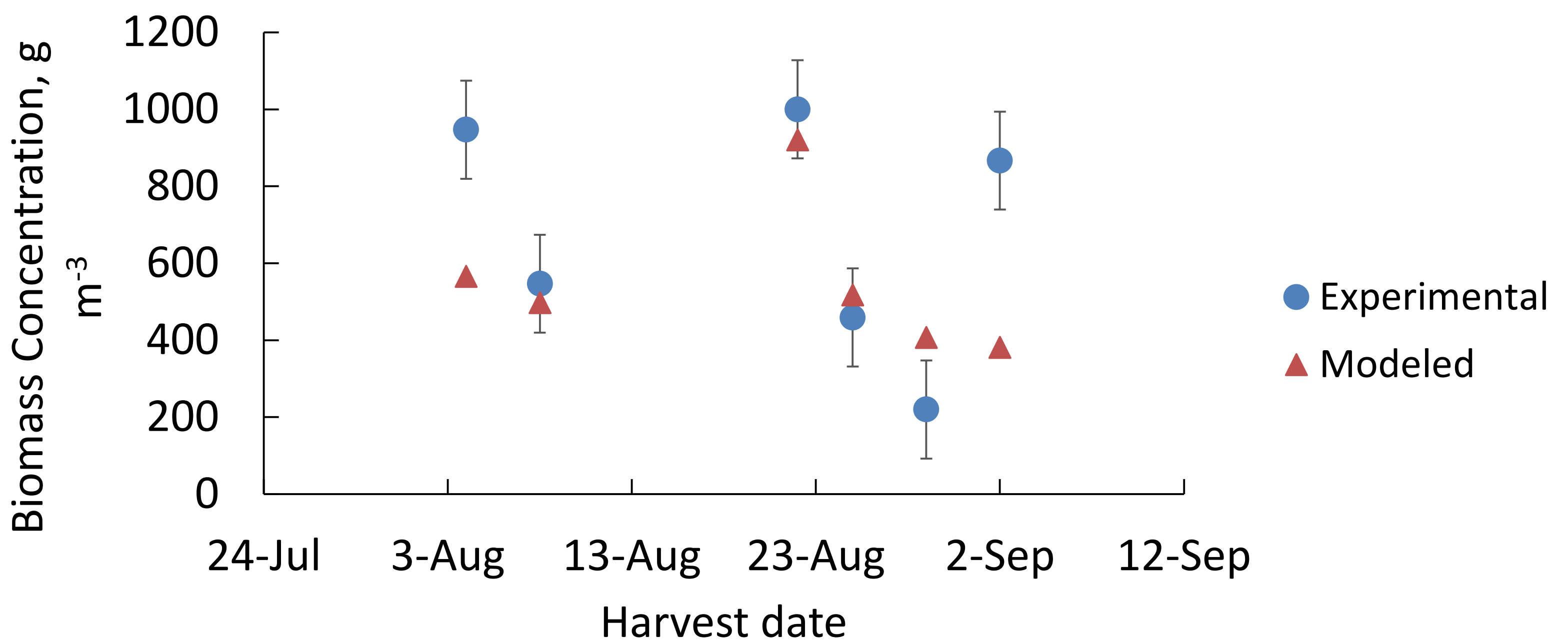
Growth Modeling: Methodology (CSU)

- Correlate growth to moles of photons incident on culture
- Adjust for:
  - Culture concentration
  - Temperature
  - Light inhibition
- Temperature modeled dynamically as well

$$\frac{dC_x}{dt} = \frac{\varphi_L \cdot \varphi_T \cdot \varphi_C \cdot P \cdot \emptyset_{photon}}{V} - D/V \qquad \rho C_p V \frac{dT}{dt} = \sum Q_n$$

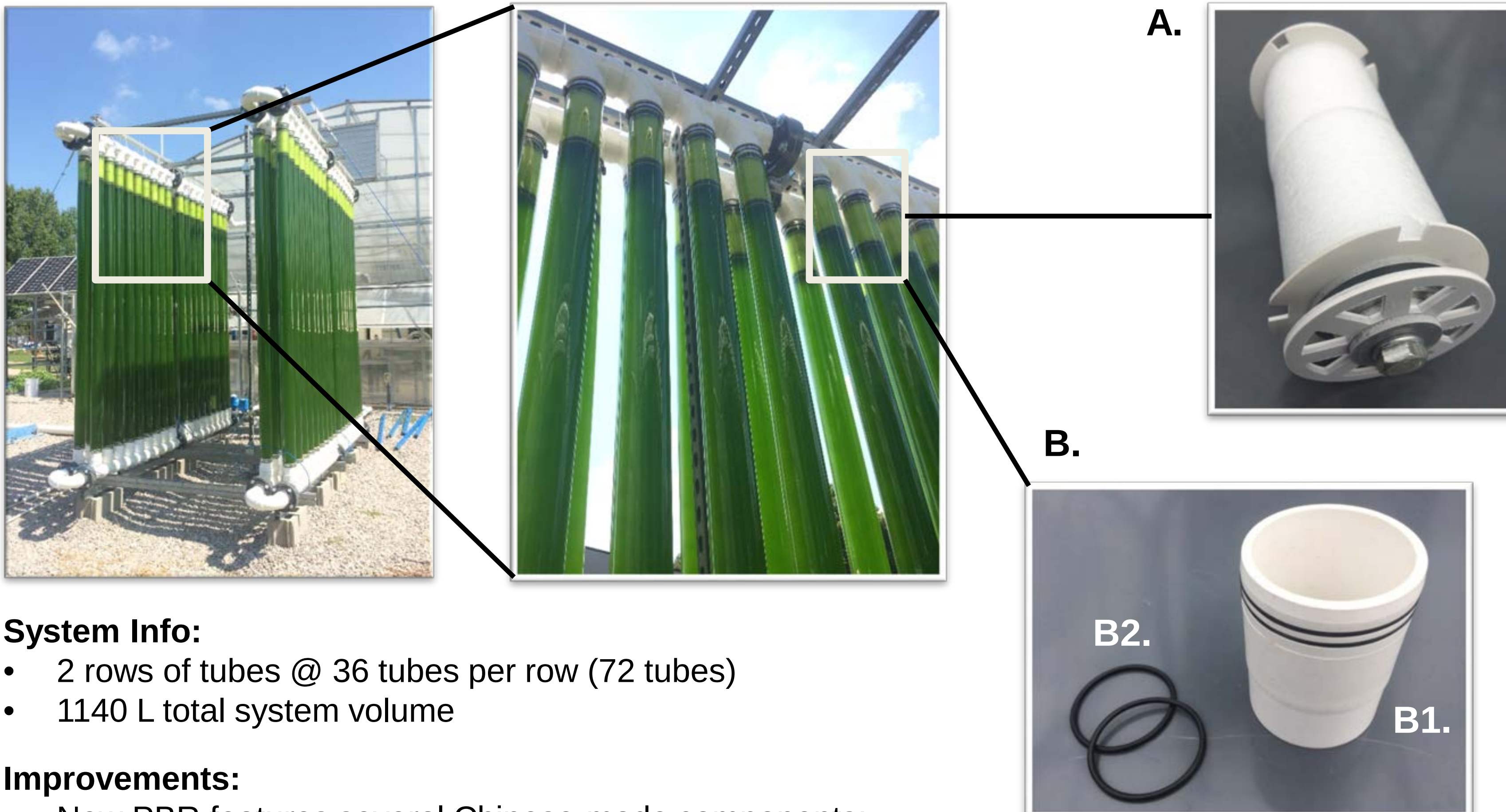
- ρ: Culture density assumed similar to water (~1000 [kg/m^3])
- $\varphi_L \cdot \varphi_T \cdot \varphi_C$ Light intensity, temperature, and concentration modifiers, [dimensionless]
- P : Rate of light incident in [uE/m^{2}s]
- $\emptyset_{photon}$: Biomass to photon correlation, g Biomass / mole photon
- V : Culture volume [m^3]
- D : Biomass loss rate, a function of temperature, light intensity, and mass of biomass in system, g/s
- $\frac{dC_x}{dt}$: Time derivative of biomass concentration, [g m^{-3} s^{-1}]
- $\frac{dT}{dt}$: Time derivative of system temperature (assumed homogeneous in space) [K / s]
- $\sum Q_n$: Sum of thermodynamic fluxes, [W/m^2 * area] → [Watts]
- C_p : Specific heat of the culture, assumed similar to water

Growth Modeling: Results in Progress



- Preliminary fitting gives mixed results
- Much more to be done in terms of model refinement and data fitting

Task 3: Construction of Updated Cyclic Flow Photobioreactor



System Info:
- 2 rows of tubes @ 36 tubes per row (72 tubes)
- 1140 L total system volume

Improvements:
- New PBR features several Chinese-made components:
  - Pipe-cleaning pigs (**A**) are now mass produced.
  - PVC stubs (**B1**) used to mount the PET tubes now utilize rubber O-rings (**B2**) instead of the previously used rubber bands, creating a more leak resistant connection.
- Improved gas delivery system with more consistent bubble column.

Task 3: Installation of Ponds

- *4 x 1100 Liter raceway ponds were installed and commissioned in first week of September 2017, along with 200 Liter seed pond*
- *Total growing capacity now > 8,000 Liters:*
  - *2 x 1200 L cyclic flow*
  - *4 x 1100 L ponds*
  - *1 x 200 L seed pond*
  - *2 x 150 L seed reactor*
  - *1 x 800 L Varicon biofence PBR*

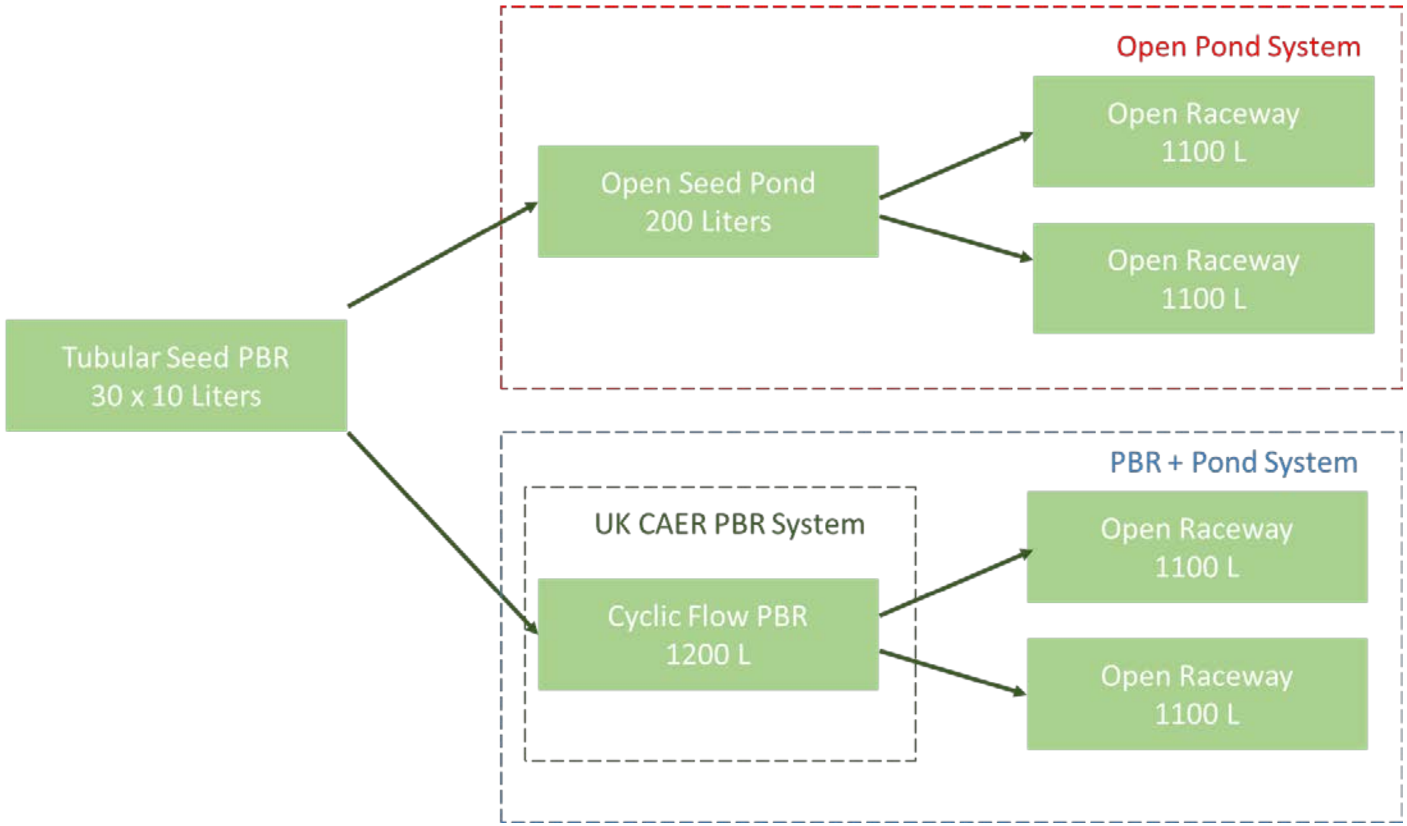
Ponds and cyclic flow PBR installed at UK CAER (10/6/2017)

Installation of Ponds: Algae Lab Systems (ALS) Water Quality Monitoring

- *Latest technology integrated with growth systems to continuously monitor temperature, pH, dissolved oxygen, and optical density*
- *ALS Spark boxes are modular, swappable, and commute wirelessly to a central hub to facilitate data visualization and export*
- *Representatives from Commercial Algae Professionals and Algae Lab Systems were on site to help with the installation and to train CAER research staff*

Clockwise from top left: ALS Spark box, software interface, wireless calibration of probes, ALS and Commercial Algae Professionals working on system installation

Growth Comparison Study

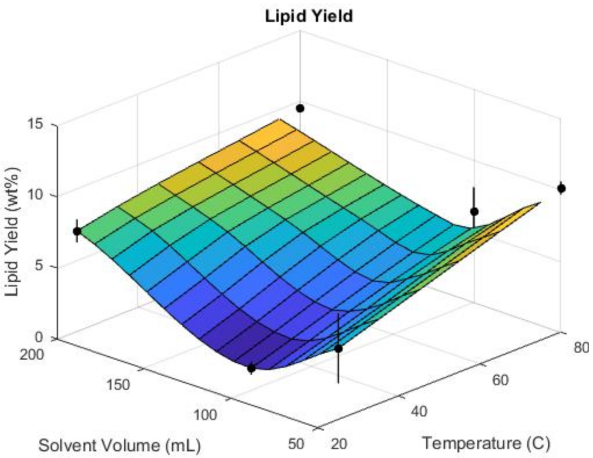


<u>Operating Conditions</u>

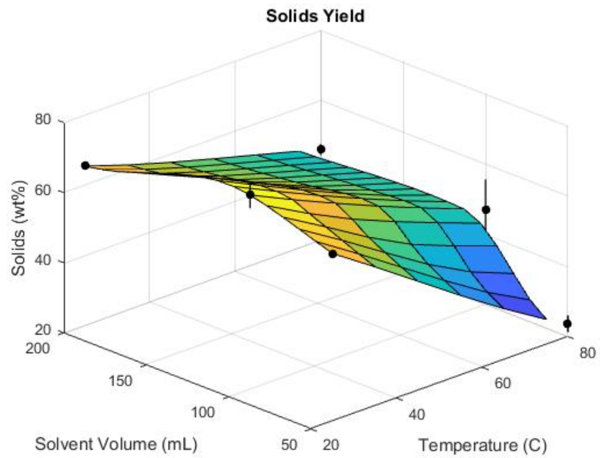
- Open Pond System seeded from seed pond and operated traditionally in semi-batch mode, with harvesting and dilution from 0.8 g/l to 0.2 g/l
- PBR + Pond system will be harvested at 0.8 g/l to 0.1 g/l with an additional ‘over seed’ of 0.1 g/l from PBR
- PBR system will then be harvested to match the other systems at 0.2 g/l
- Similar data sets will be maintained for all systems

Task 4: Optimization of Algae Fractionation Process

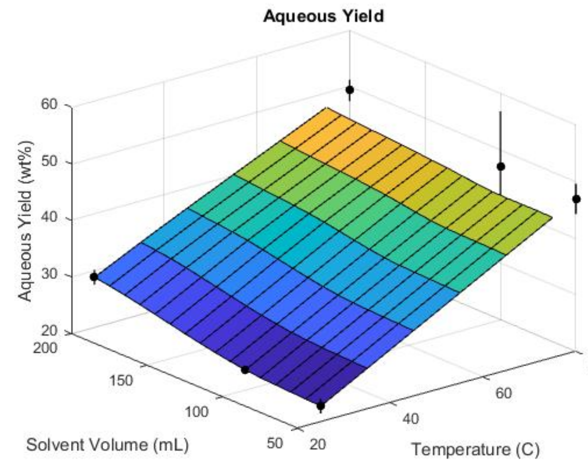
- Lipids are isolated from wet algae biomass via in situ transesterification/esterification
- 5 wt% HCl in methanol is used as pretreatment solvent (pH 1-2)
- Lipids recovered via hexane washing, solids via filtration
- Aqueous phase contains mainly dissolved sugars (with some protein)



Lipids



Residual solid biomass



Solid from aq. phase

- Yields of residual solid biomass and dissolved matter in aqueous phase can be tuned to a large degree
- Additional experiments will include variation of acid concentrations and complete analysis of products

Summary of Progress to Date

- Work commenced on building model for algae growth in cyclic flow PBR
- 1100 L cyclic flow PBR installed at UK CAER, together with 4 x 1100 L ponds and monitoring equipment
- Culturing study initiated in mid-September
- DoE underway, with goal of optimizing wet lipid extraction process

Next Steps

- Work to continue on development of engineering process model
- Continuation of productivity study for as long as weather allows (with start-up again at CAER in April)
- Completion of biomass fraction study, including analysis of fractions (fermentable sugar and lipid yields)

- NB. Productivity study to be transferred to East Bend in June 2018 (EB maintenance shutdown scheduled for March-May)

Acknowledgements

- Department of Energy / National Energy Technology Laboratory
- University of Kentucky:
  Michael Wilson, Dr. Jack Groppo, Stephanie Kesner,
  Daniel Mohler, Robert Pace, Thomas Grubbs
- Colorado State University:
  Dr. Jason Quinn, Sam Compton
- Algix:
  Dr. Ashton Zeller, Ryan Hunt
- Duke Energy:
  Doug Durst