Improving the cost-effectiveness of algal CO2 utilization by synergistic integration with power plant and wastewater treatment operations

Department of Energy Cooperative Agreement No: DE-FE0032098

2024 NETL Annual Review Meeting
Pittsburgh, PA

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Project Overview

- DOE Funding Program DE-FOA-0002403: *Engineering-Scale Testing & Validation of Algae-Based Technologies & Bioproducts Area of Interest 1 (AOI 1)*
- Upscaling and integrating unit processes for algal carbon capture at a coal power plant site
  - 180 m^2 outdoor raceway ponds with ability to use wastewater nutrients (and makeup water)
- *End of Project Objectives & Goals:*
  - BP1 Goal- New cultivation system installed & operational achieving >10 $g/m^2/d$ productivity
  - BP2 Goal- Improved operations with productivity > 14.3 $g/m^2/d$ and wastewater nutrients to reduce costs
  - Project End Goal: Techno-economic analysis at 5000-ac scale with a minimum selling price below market value of protein concentrate (and $0 CO_2 capture credit)

Budget Period	Primary Work	Start	End	Budget
1	Design and Construction	10/1/2021	9/30/2023 (6-mo Extension)	$1,897,532
2	Testing and Optimization	10/1/2023	3/31/2025	$601,564

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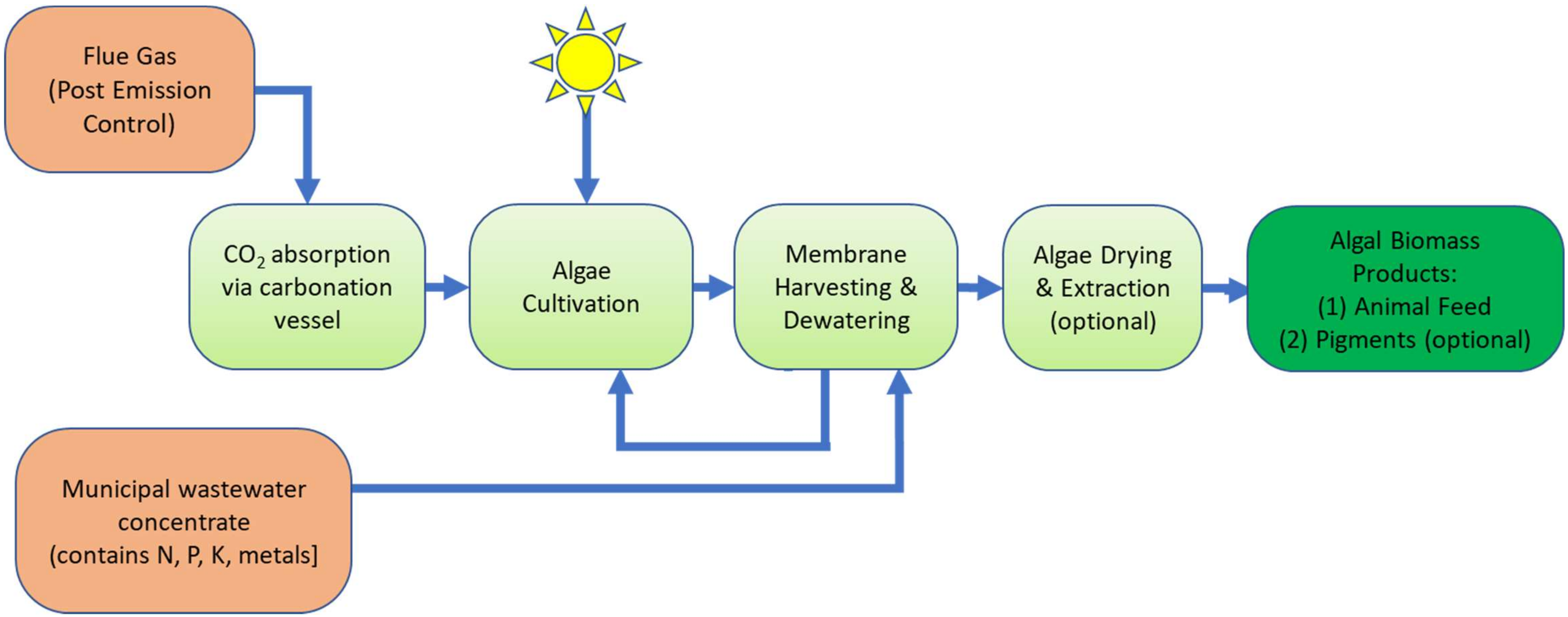
Technical Approach

Project Strategy: Combination of Key Advantages

- Best in Class Algae Cultivation System from GAI — GLOBAL ALGAE
- First Demonstration with GAI System Using Coal Flue Gas — City Water Light and Power (Springfield, IL)
- Improvement of Economics with Use of Wastewater Nutrients and Animal Feed Testing — UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

Technology Background- Simplified Block Flow Diagram



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Technical Approach

Complete

Task / Subtask	Milestones
1/1.1	Submit Updated Project Management Plan (PMP)
1/1.2	Submit Initial Technology Maturation Plan (TMP)
2	Cultivation system installed and operational achieves at least 10 g/m2/d productivity with coal flue gas CO_2
3	Absorber system installed and operational and achieves at least 75% carbon capture efficiency
4	Harvesting and drying system installed and operational and produces algae powder with less than 10% moisture content
5	Algae protein meal with at least 50% protein
6	Demonstrate ability to replace at least 50% of nutrients in algal inoculation cultures
7	Interim TEA and LCA confirming costs for baseline performance
8.1	Integrated system has average CO_2 capture efficiency of >80%,
8.2	Cultivation system has an average productivity of 14.3 g/m^2d with coal flue gas CO_2
9	Demonstrate ability to use power plant waste heat to extend algae growing season and increase cold weather productivity
10	Determine projected value of algal biomass based on live chicken digestion tests
11	Final TEA incorporating averages of key performance parameters projects a required selling price that is less than the market price of the protein concentrates at a scale of 5000-acres with $0 credit for CO2 capture and mitigation
12	Final LCA incorporating averages of key performance parameters projects at least a 50% reduction in GHG for the target products

Project Overview

Overall plant site has

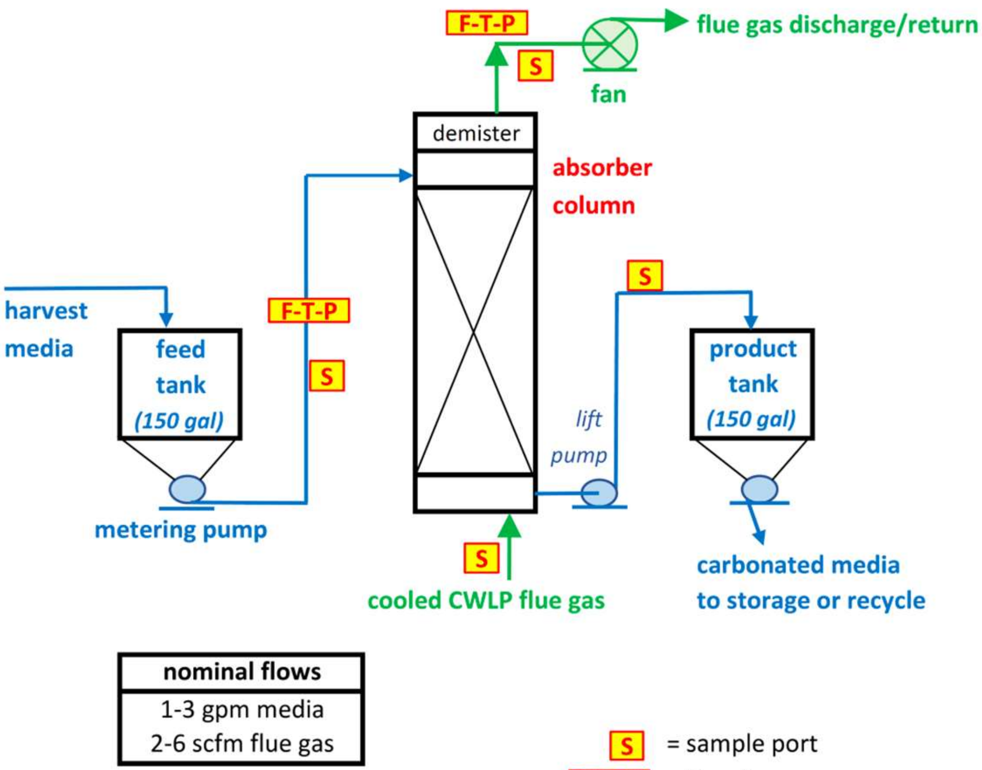
- Existing 500 MW coal power plant
- Large pilot for amine CO_2 capture (10 MW)
- Algae pilot for biological CO_2 capture (< 0.1 MW)

Project Achievements

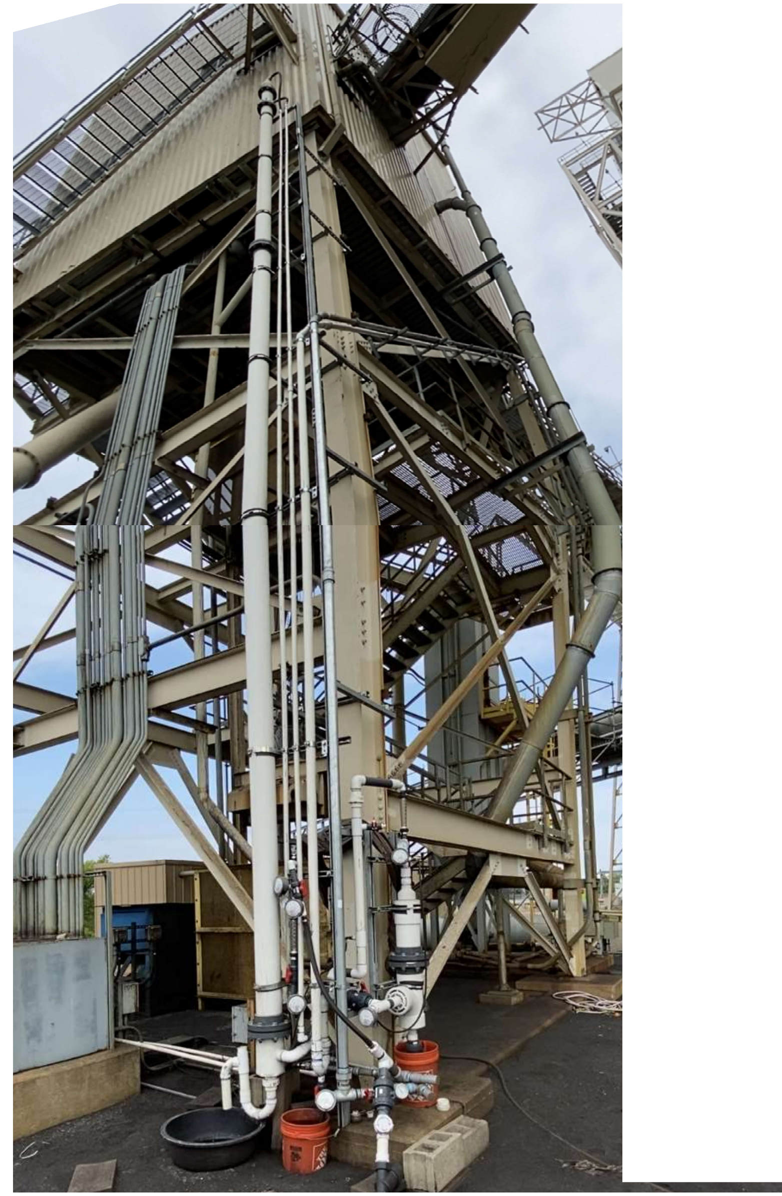
Design Layout

Constructed System

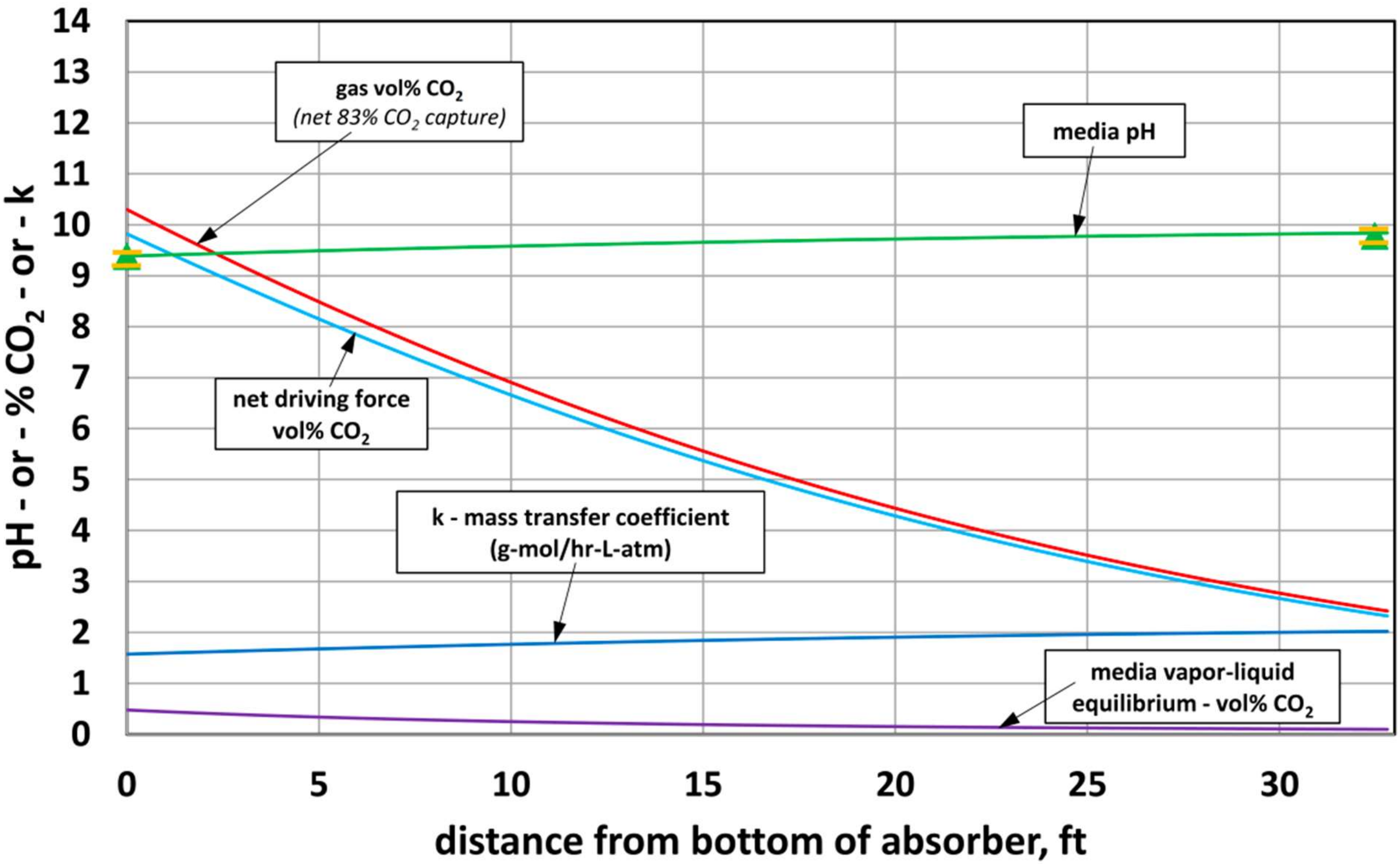
Project Achievements Flue Gas Absorber System Design and Construction



Process Flow Diagram



Project Achievements- *83% CO_2 Capture Achieved Based on pH Change Model*

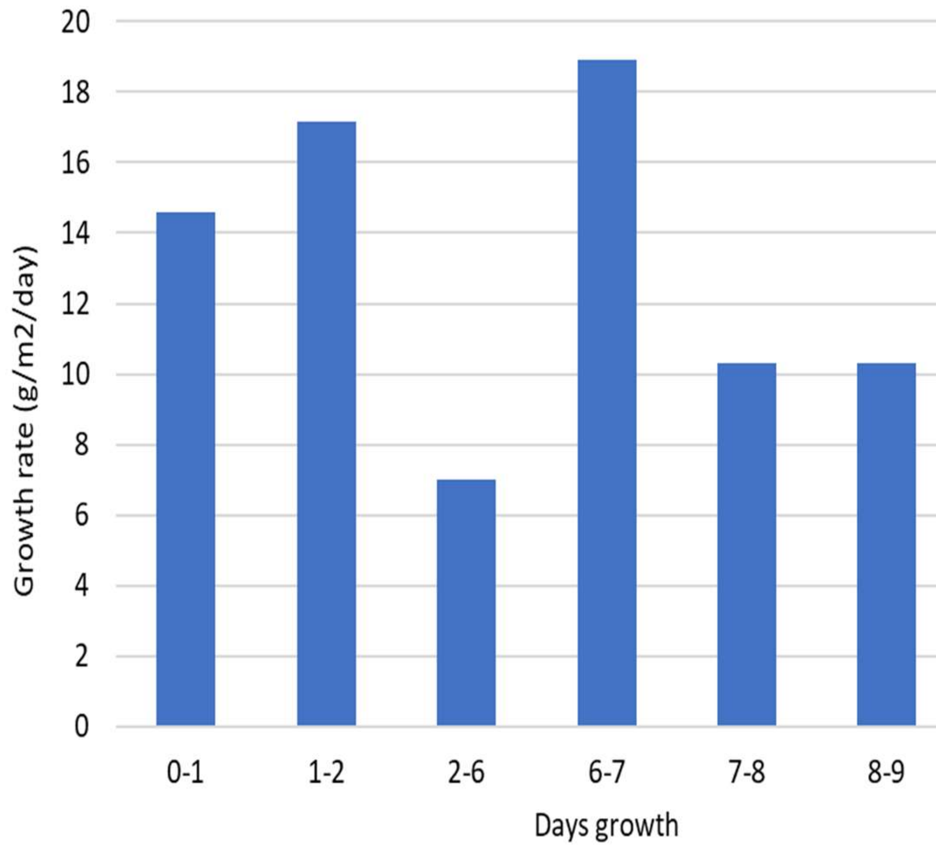


$CO_2 + H_2O \rightarrow HCO_3^- + H^+$

Project Achievements- Average Algae Productivity >10 g/m2-day Initial Target

Small Raceways Used for Culture Upscaling

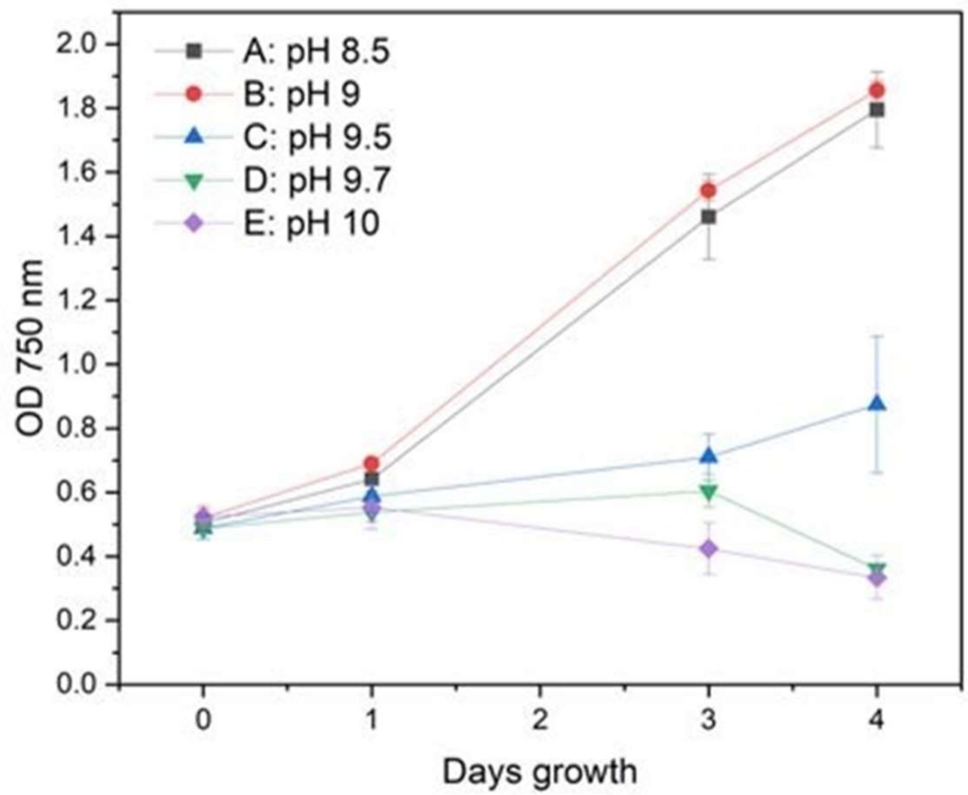
Larger Raceways Operated with Flue Gas Integration



Typical Algae Biomass Productivity for Batch Operations

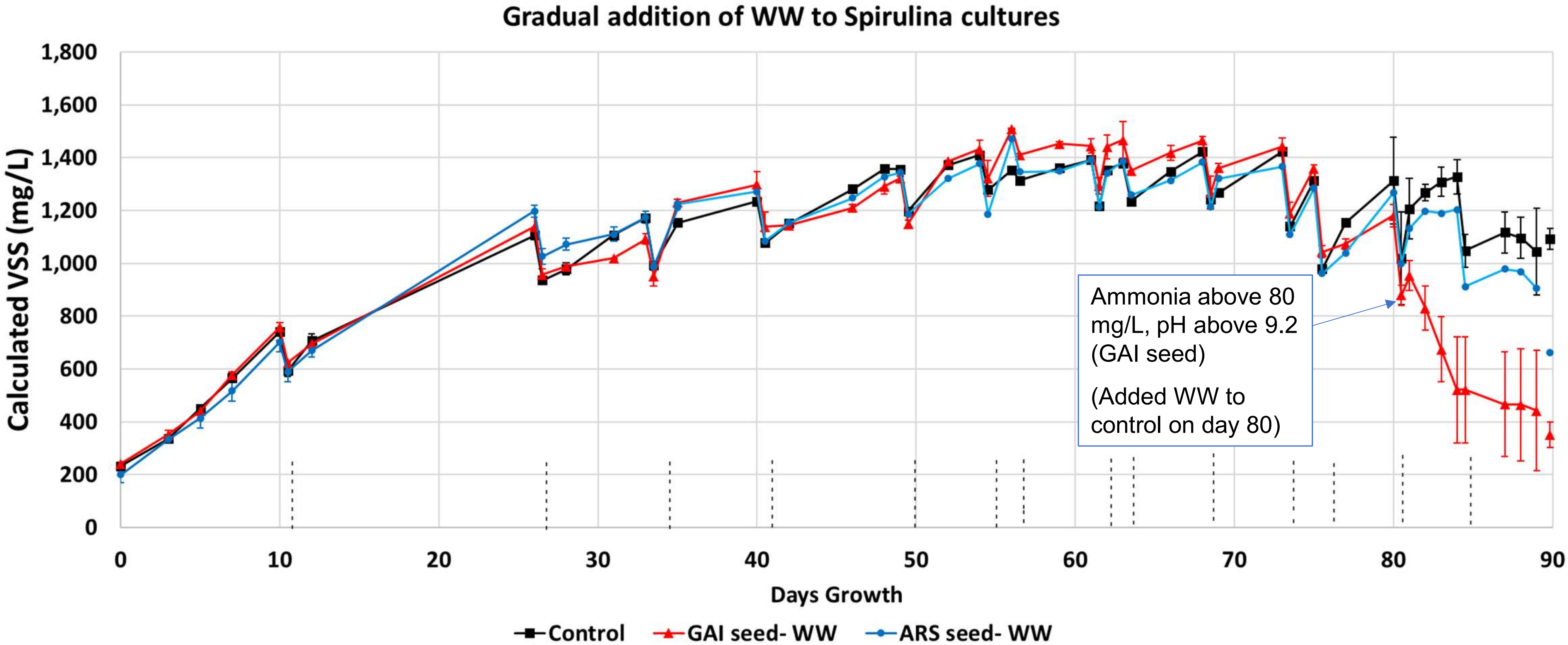
Project Achievements- *Understanding relationship of pH & ammonia concentration*

- *Spirulina* selected species for high pH tolerance
  - High pH good for CO2 capture and less contamination
  - High pH can restrict using wastewater b/c NH_3 inhibition
- Concentrated wastewater N form is typically in the form of ammonia (NH_3)
- Experiments comparing algae growth at different combinations of levels of pH and NH_3 ($pk_a = 9.24$)
  - Data shown for 135 mg/L NH_3
  - Growth retarded @ pH 9.5 and above
- When operating > pH 9.3 need to control delivery of NH_3 to match algal uptake
  - Typical algal biomass is 10-15% N
  - Recommend NH_3 <80 mg/L NH_3 above pK_a
- May be possible to gradually acclimate algae to higher NH_3 concentrations



Achievements- Long-term cultivation used >90% of N from WW (gradually added)

Demonstrated similar growth of *Spirulina* with control media (Zarrouck's) and gradual addition of wastewater
Recommend keeping total ammoniacal nitrogen (TAN) below 80 mg/L and/or pH below 9.2 to avoid NH_3 toxicity.



Project Achievements

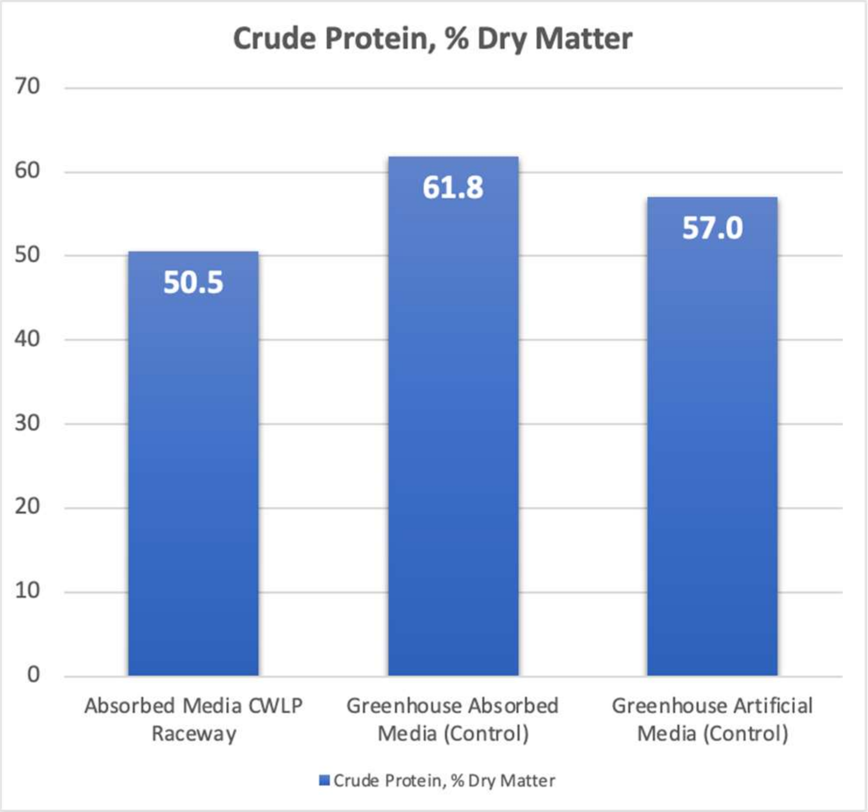
Water quality tests at end of long-term WW cultivation showed no significant accumulation or lack of key nutrients
Wastewater has potential to replace more media ingredients (such as Ca and B).

Analyte	Expected in Zarrouk's	Zarrouk's (ISWS results)	Wastewater Centrate (WW)	A: Control, then WW	B: WW treat (GAI)	C: WW treat (ARS)
Barium	-	0.003	0.024	0.006	0.013	0.011
Boron	0.500	0.48	0.433	0.556	0.504	0.406
Iron	2.009	0.243	0.173	0.103	0.536	0.499
Manganese	0.502	0.305	0.01	0.14	0.016	0.042
Copper	0.020	0.011	0	0.004	0.002	0.005
Zinc	0.235	0.023	0	0	0	0.095
Silicon	-	0.227	9.67	4.45	7.08	6.17
Calcium	10.905	10.4	33.4	5.85	4.74	4.53
Magnesium	19.722	18.5	3.71	18.9	25.1	25.3
Sulfur	184.007	142	11	132	141	134
Phosphorus	88.913	152	32.5	64.3	18.7	19.4
Potassium	336.600	608	146	608	634	616

Animal Feed Testing

Feed Purity Testing Comparison

Critical Metal Levels	Sampled Range of Current Animal Protein Products	Project Sample
Arsenic (ppm)	0 - 8.34	Below Detection Limit (<0.020)
Cadmium (ppm)	0 - 1.63	Below Detection Limit (<0.0043)
Lead (ppm)	0 - 1.88	Below Detection Limit (<0.019)



Metals Analysis:

Initial testing of algae produced with absorbed flue gas media.

Protein Analysis:

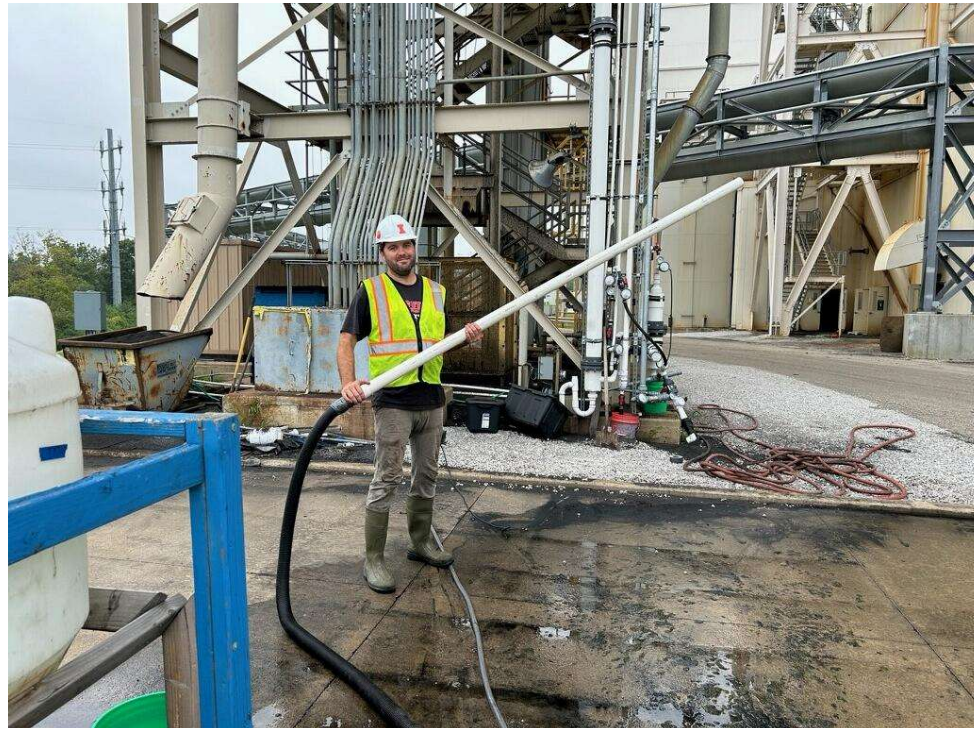
Initial testing of algae strain has shown all growth medium produce algae with protein above the 50% target.

Animal Sciences
COLLEGE OF ACES

Project Achievements

Many Lessons Learned in Field Operations:

- Unexpected weather can cause problems
  - Unexpected heavy rain can cause culture to become too dilute → culture crash
  - High evaporation w/o rain can starve pumps→ foaming, low mixing, crash
- Coal dust didn't reduce growth directly but negatively affected some pumps
- pH balancing with NH_3 can be challenging
  - If culture starts dying, NH_3 can be released which leads to a downward death spiral
- Cleaning tanks and raceways is important and requires both diligence and creativity



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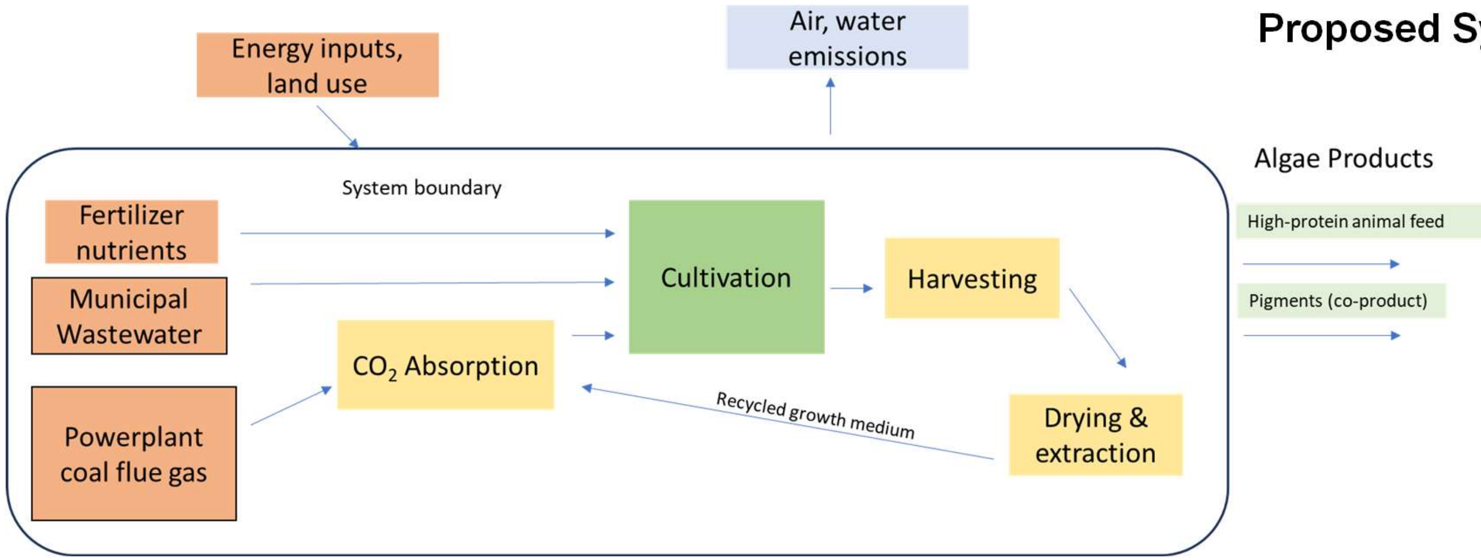
Techno Economic Analysis

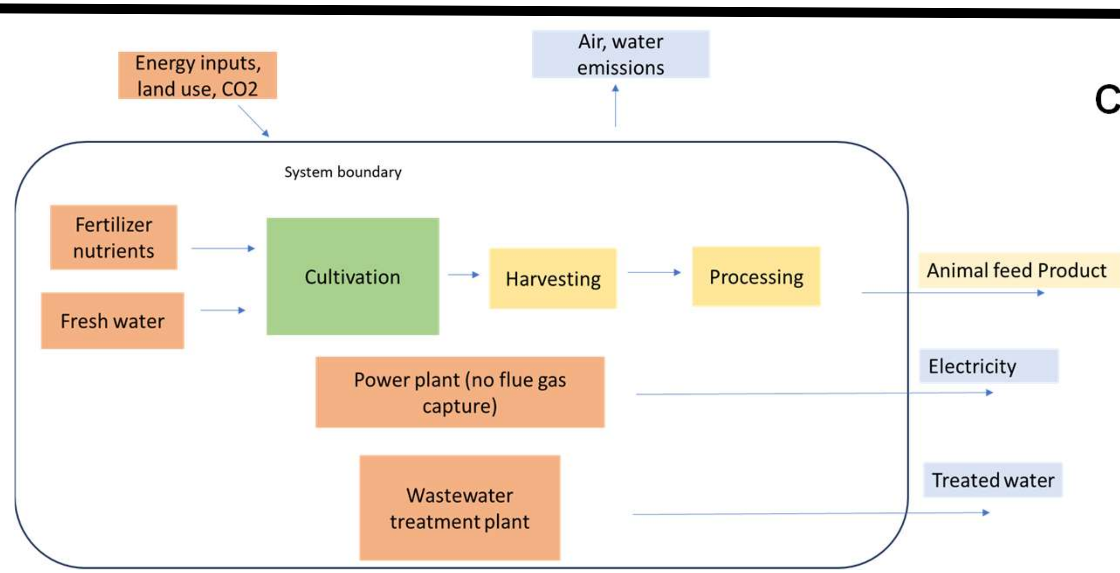
and

Interim Life Cycle Analysis

Proposed System



Comparison System



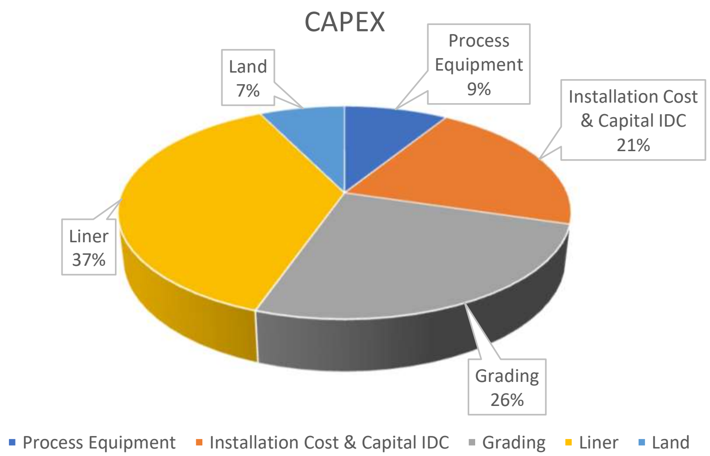
Baseline TEA for 5000-acre Algae Farm in IL

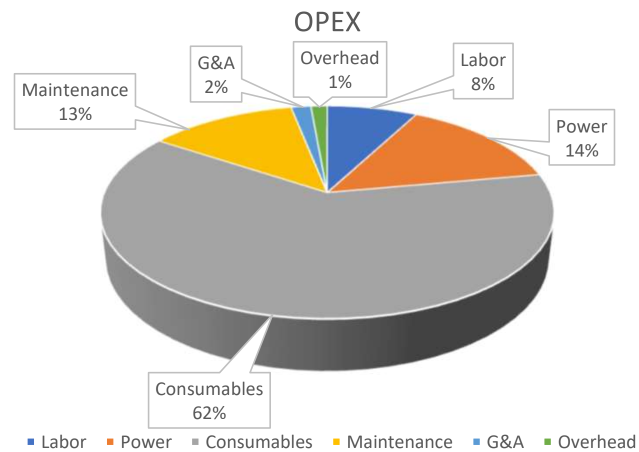
Algae carbon capture could be limited by local WW nutrients:

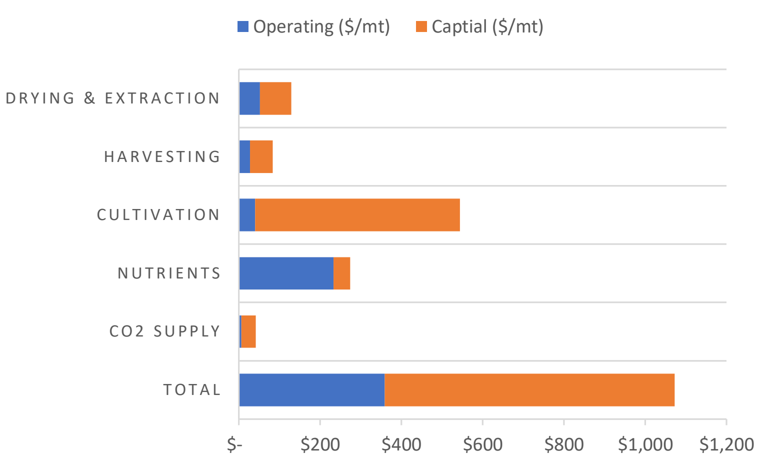
Springfield Sanitary District – 40 MGD plant w/ 6 ton N/day (vs ~20 tpd needed)

Parameter	5000-acre scale
Algal Culture	*Spirulina*
Gross / Net Power Plant Capacity (MW) – CWLP Dallman Unit 4	230.1/200
Power Plant CO2 emission (tonnes/MWh)	0.76
Power Plant Annual CO2 Emission (tonnes/year) (based on peak load)(capacity factor: 0.85)	1.53 Mil./1.3 Mil.
Target Carbon Dioxide Removal (%)	8.5% / 10 %
Avg. Algae Productivity (g/m^2-d)	10.4
Algae Cultivation Area (Acres)	5000
Annual Avg. Algal Biomass Production (dry tonnes/yr)	74,000

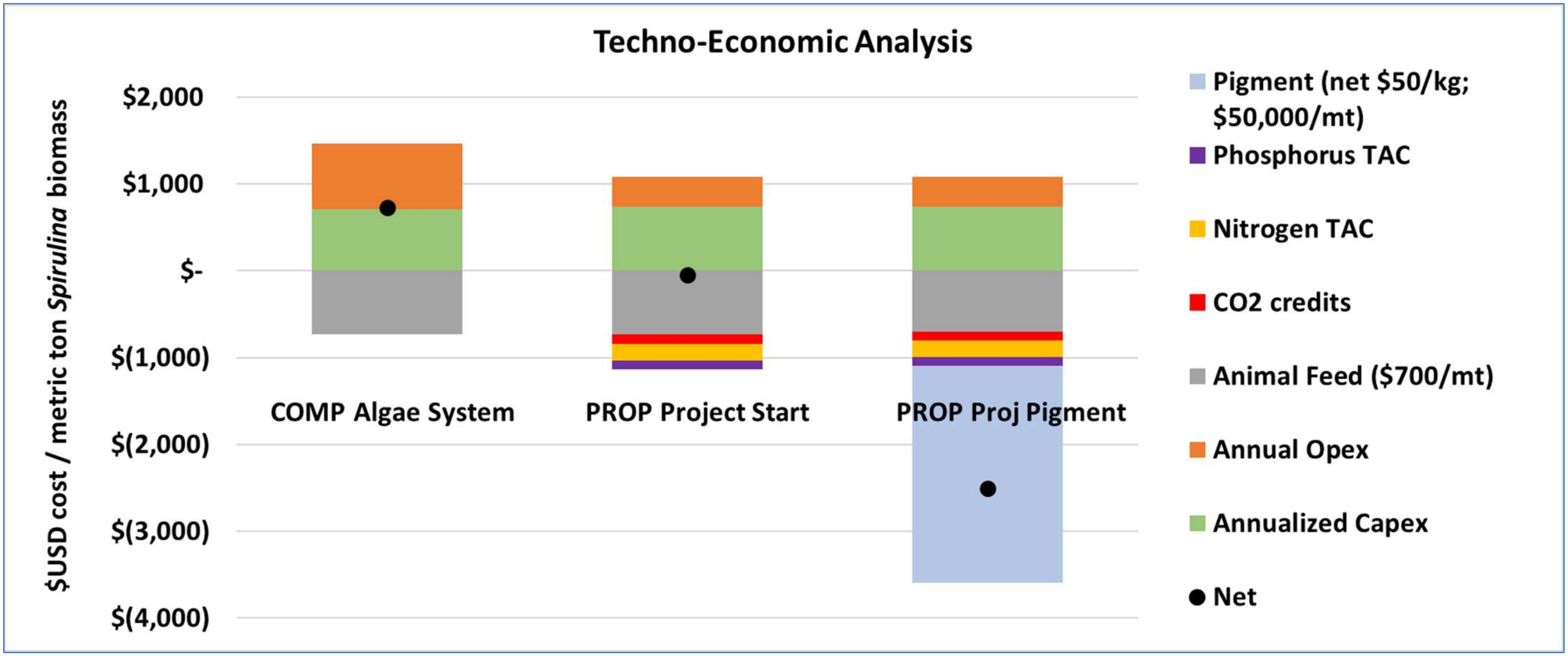
Preliminary Estimates on CAPEX & OPEX







- Potential revenue sources: Wastewater nutrient removal > animal feed > CO_2 credit
- Further improvements in lowering costs and increasing productivity possible
  - Extraction of other high value algae bioproducts (antioxidants, pigments, PUFA, fatty acids)
  - Reduced energy inputs for algae media mixing and harvesting
  - Potential improvements included in current on-going projects

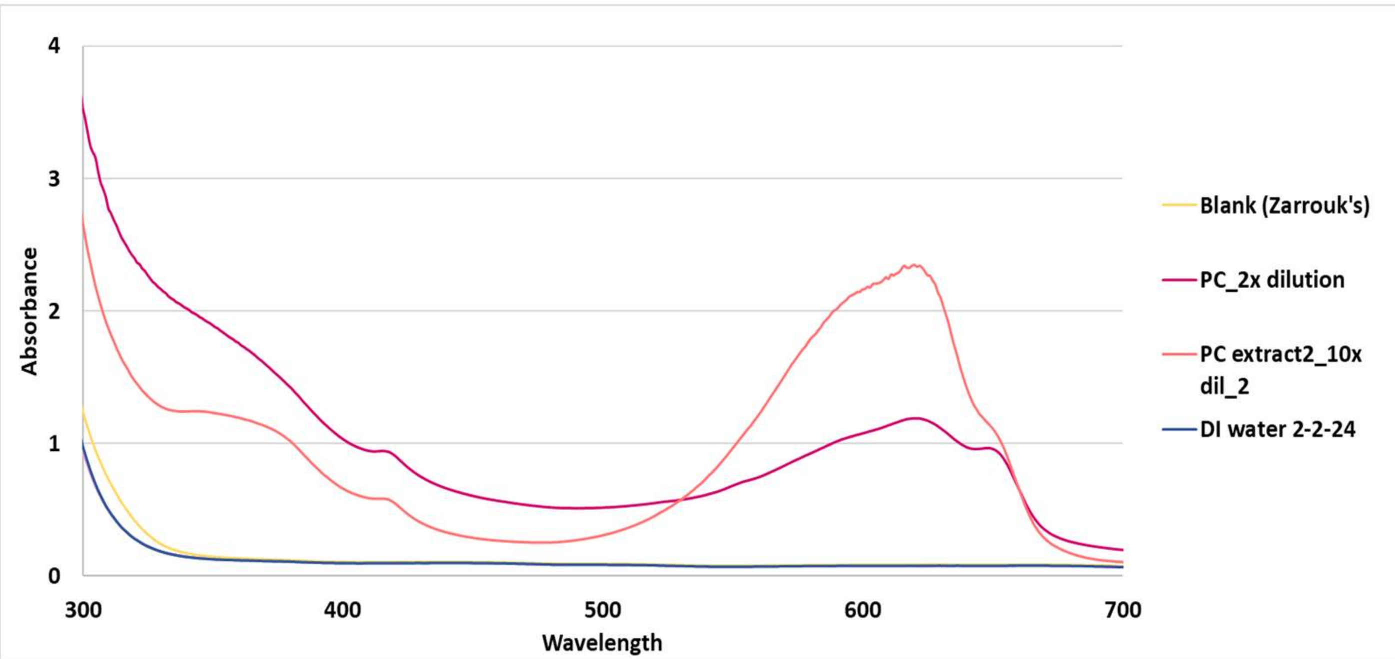


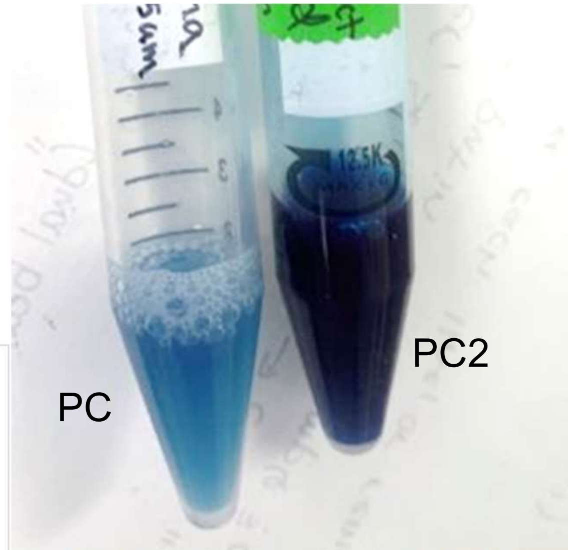
Cost per metric ton of *Spirulina* biomass, in comparison baseline algae system, proposed project start, and the proposed project system with extraction of phycocyanin pigment. TAC= Treatment Avoidance Credit.

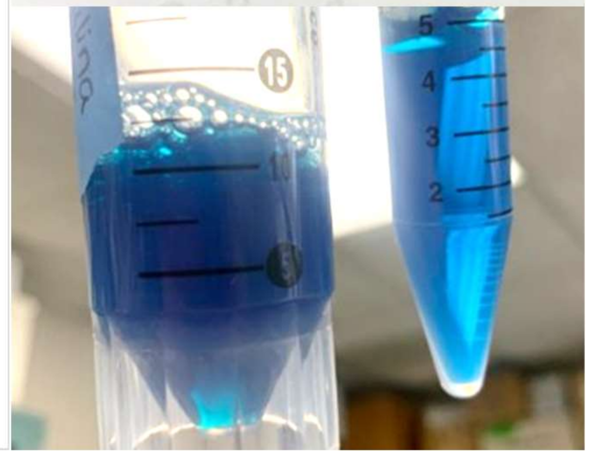
Phycocyanin Analysis and Separation

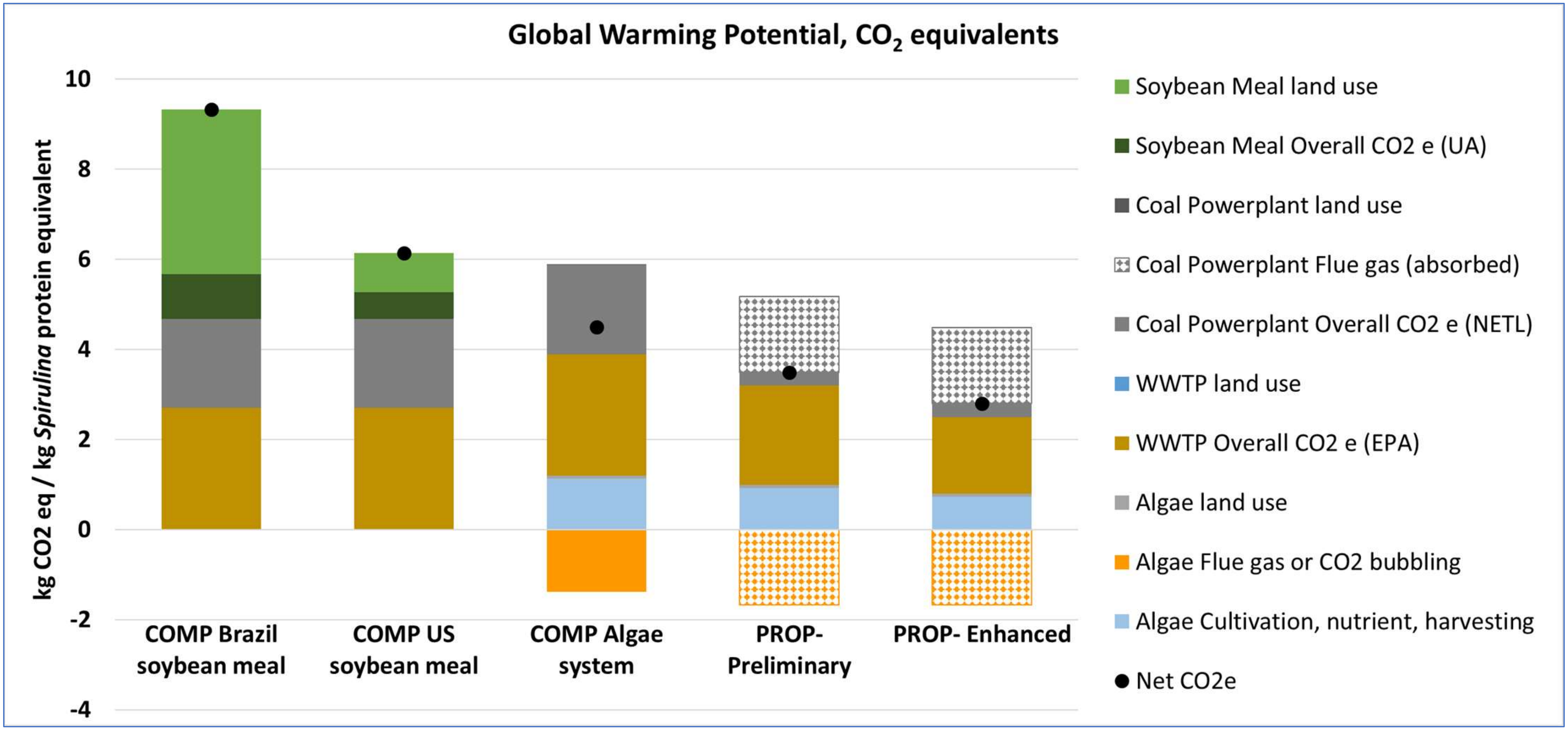
Phycocyanin (PC) pigment was passively separated from concentrated biomass by cooling.

UV-Vis results showed ~40 g/L PC content in the extract.









LCA results showing pathway to >50% reduction in GWP (CO_2e) for proposed (PROP) product system (1 kg *Spirulina* =1.22 kg soybean meal). Pigment extraction not included in LCA.

Summary

- **Project Status:** Operation of a new engineering-scale algae system at a power plant is underway
- **Key Project Advantages:**
  - Leading edge cultivation system demonstrated with coal flue gas in northern climate
  - Wastewater nutrients and pigment co-products improve TEA and LCA
- **Project Impact - Animal Feed:**
  - Live animal poultry testing
  - Economic demand: Large/growing market
  - Less land needs vs. conventional crops
  - 100% biomass use vs losses in fuel conversion

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