A highly efficient microalgae-based carbon sequestration system to reduce CO_2 emission from power plant flue gas

DE-FE0031914

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Robert Mroz, HY-TEK Bio, LLC;

Troy Hawkins, Sudhanya Banerjee, Udayan Singh, Argonne National Laboratory

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U.S. Department of Energy

National Energy Technology Laboratory
Carbon Management Project Review Meeting
Session "Capture from Industrial Sources"
August 15, 2022

Project Overview

– Funding

DOE: $3,000,000 and Cost Share: $750,000

– Overall Project Performance Dates:

Sep. 2020 to Sep. 2023

– Project Participants:

Yantao Li, Feng Chen, Russell Hill, University of Maryland Center for Environmental Science;

Robert Mroz, HY-TEK Bio, LLC;

Troy Hawkins, Sudhanya Banerjee, **Udayan Singh**, Argonne National Lab

DOE NETL Program Manager: **Lei Hong** (From Jan. 2022), **Kyle Smith** (May- Dec. 2021), **Katharina Daniels** Sep. 2020 to Apr. 2021)

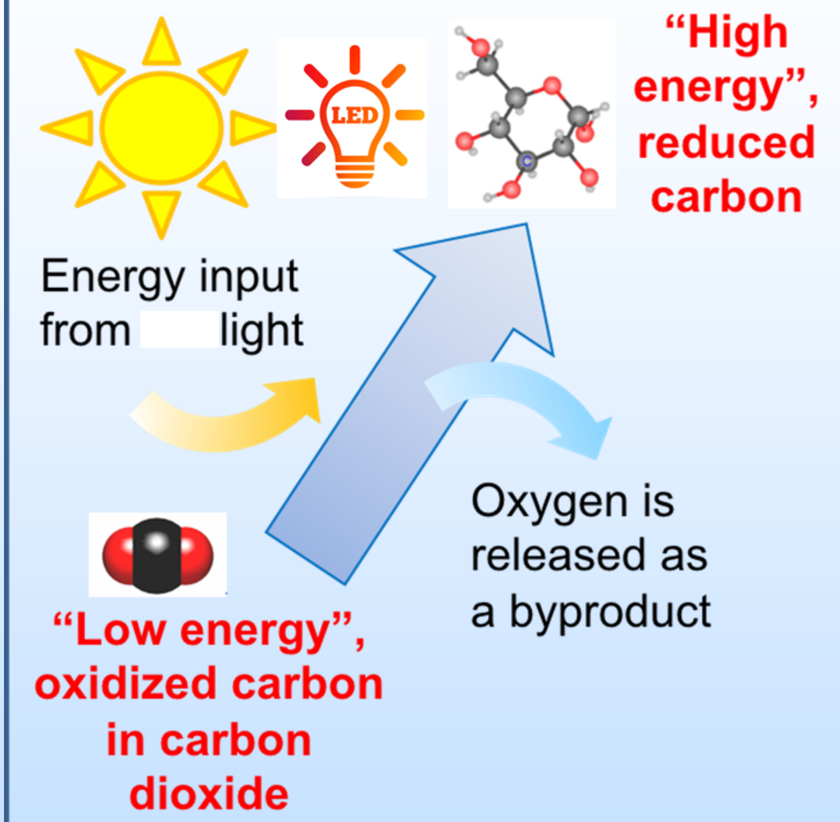
University of Maryland Center for Environmental Science HY-TEK Bio Argonne National Laboratory

Project Overview

– Overall Project Objectives

The objective of this project is to harness the power of photosynthetic microalgae to maintain a high-pH, high-alkalinity microalgal culture to create a carbon-negative system for carbon dioxide (CO_2) conversion to value-added products from power plant flue gas.

Technology Background



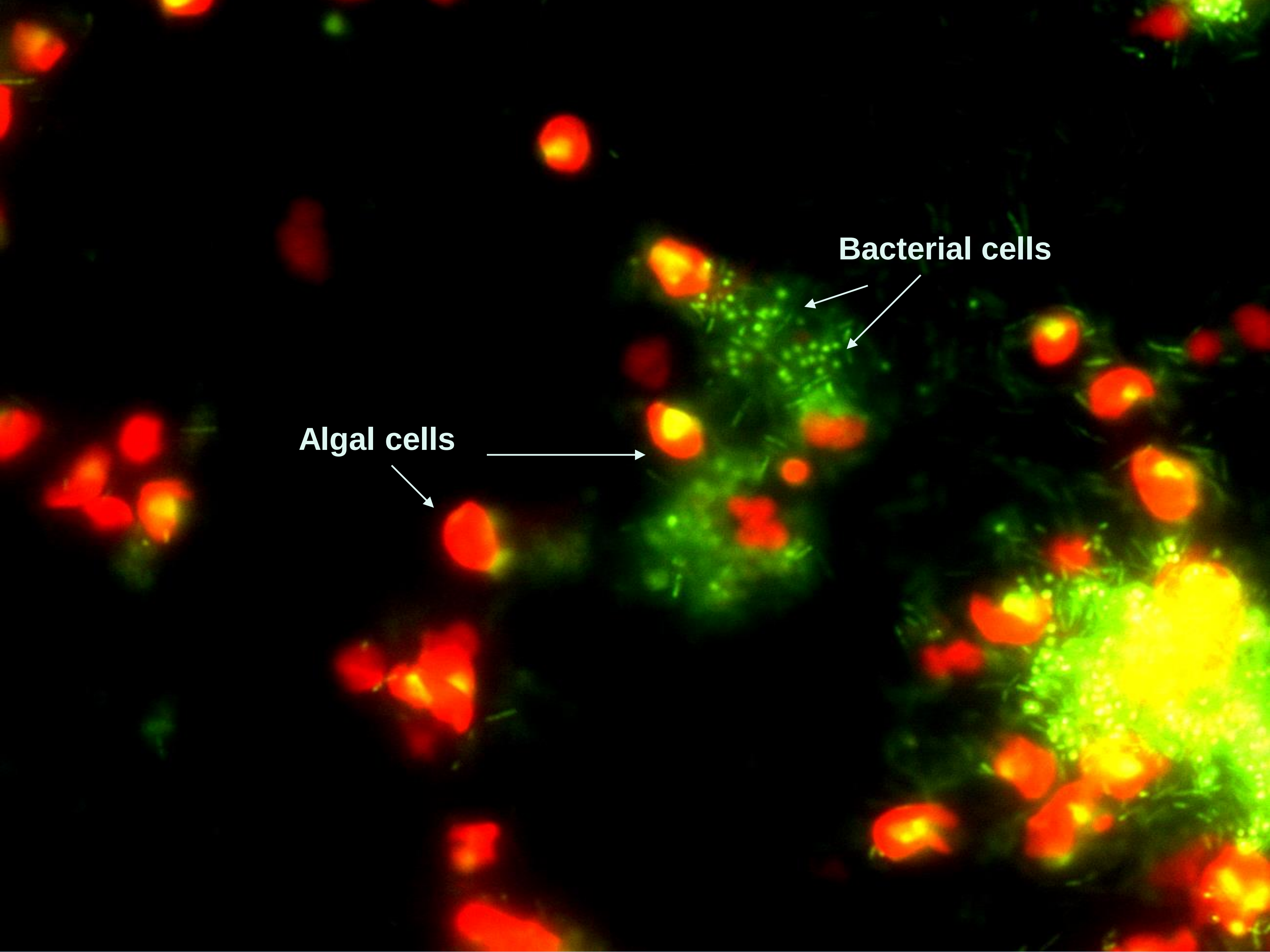
$$6\ CO_2 + 6\ H_2O \rightarrow C_6H_{12}O_6 + 6\ O_2$$

Williams, M.E. (July 31, 2016). Carbon-Fixing Reactions of Photosynthesis. The Plant Cell, doi/10.1105/tpc.116.tt0716.

Byrne 2017

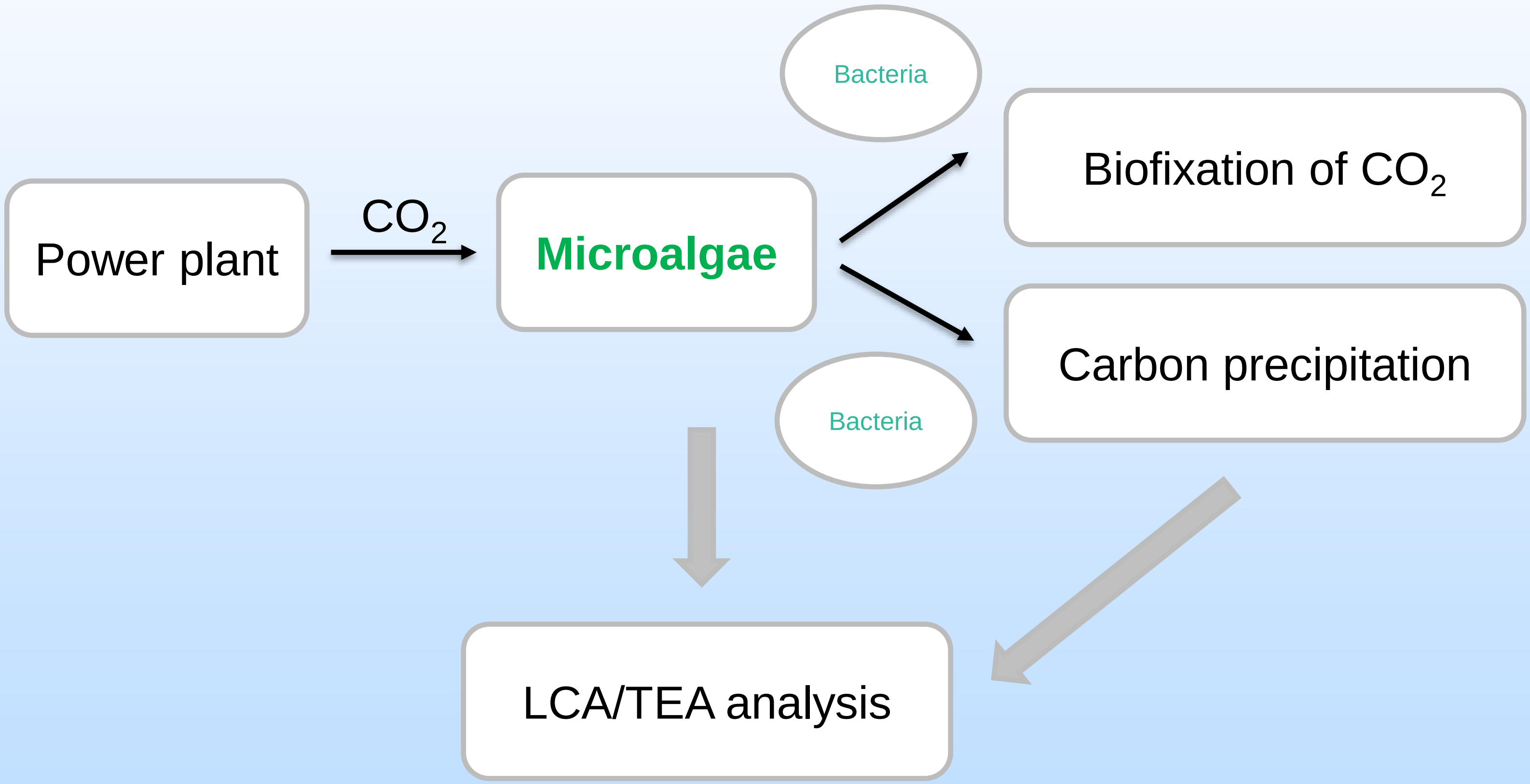
1 g algal biomass produced will consume 1.83 g CO_2.

Algal biomass has multiple applications.


Bacterial cells
Algal cells

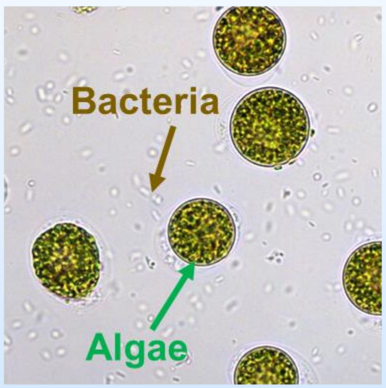
Technology Background

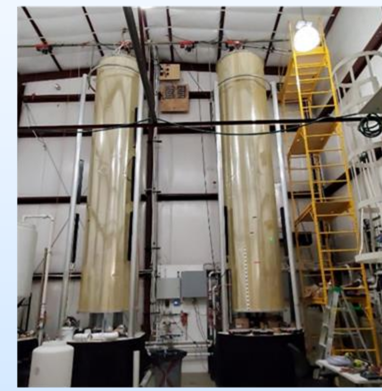
Microalgae Driven Carbon Capture



Technology Background: Proposed Technology Readiness Level

Basic principle TRL 1	*Baseline* Lab scale TRL 4	Pilot scale TRL 6	*End goal* Full scale TRL 7



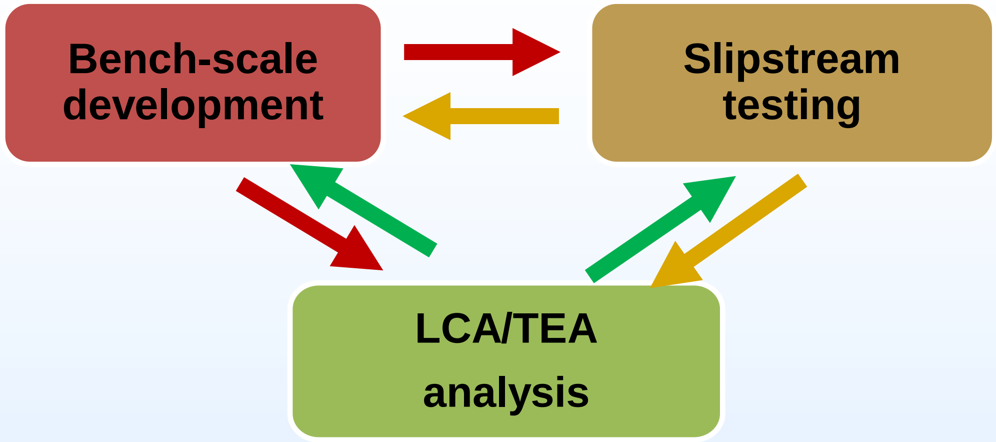


- **Algae-bacteria cell-cell interactions**
- **Lab-scale Reactors (1-10 L)**
- **Pilot-scale reactors (500 L each)**
- **Full-scale reactors (6,800 L each)**

10^{-15} — 10^{1} — 10^{3} — 10^{4} (L)

System volume

Technical Approach/Project Scope



Bench-scale development of a saltwater and a freshwater algal system (UMCES)

- Subtask 2.1; 3.1; 4.1: Saltwater algal carbon sequestration system **(Li and Hill)**
- Subtask 2.2; 3.1; 4.1: Freshwater algal carbon sequestration **(Chen and Hill)**

Slipstream testing of the algal carbon sequestration system (HY-TEK Bio)

- Subtask 2.3; 3.2; 4.2: Slipstream test on strains IMET1 and HTB1 at 500 L **(Mroz)**
- Subtask 3.3; 4.3: Slipstream test on algal strains IMET1 and HTB1 at 6,800 L **(Mroz)**

Development of TEA and LCA models to evaluate and guide (Argonne)

- Subtask 2.4; 3.4; 4.4: Perform TEA and LCA analysis **(*Hawkins and Banerjee*)**

Progress- Budget Period 1 (Finished with 3-month NCTE)

Subtask 2.1 **- Develop a saltwater algal carbon sequestration system at lab scale**

Milestone 2.1 Achieve >90% mitigation efficiency of each algae at lab scale. M15

Subtask 2.2 **- Develop a freshwater algal carbon sequestration system at lab scale**

Milestone 2.2 Achieve >90% mitigation efficiency of each algae at lab scale. M15

Subtask 2.3 **– Initial slipstream testing at 500-L scale**

Milestone 2.3 Achieve >90% mitigation efficiency at 500-L scale. M15

Subtask 2.4 **- Develop the frameworks for the TEA and LCA models**

Milestone 2.4 Develop frameworks for the TEA and LCA models. M15

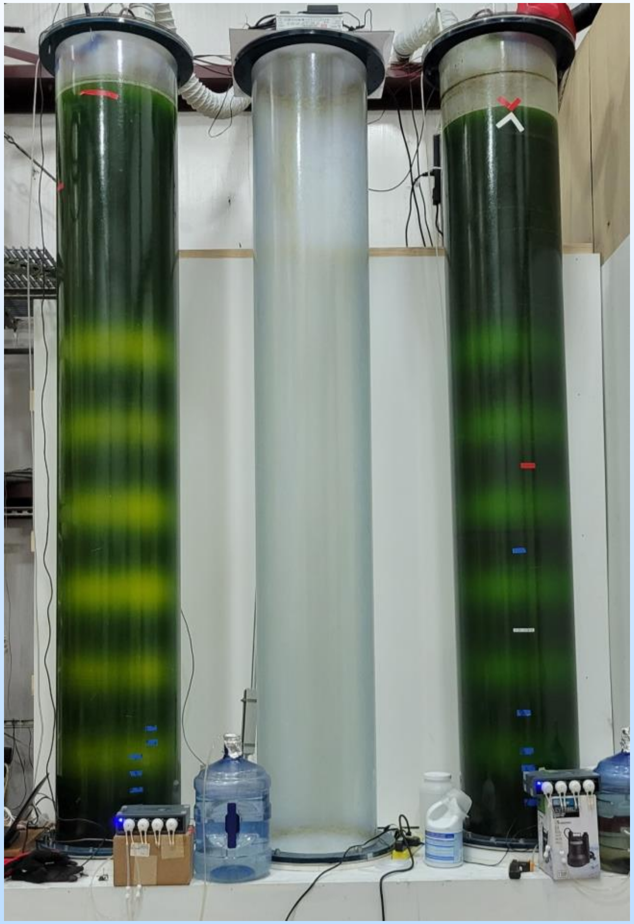
HY-TEK Bio's Facility at the Back River Waste Water Treatment Plant

Current HTB site in operation for more than 8yrs

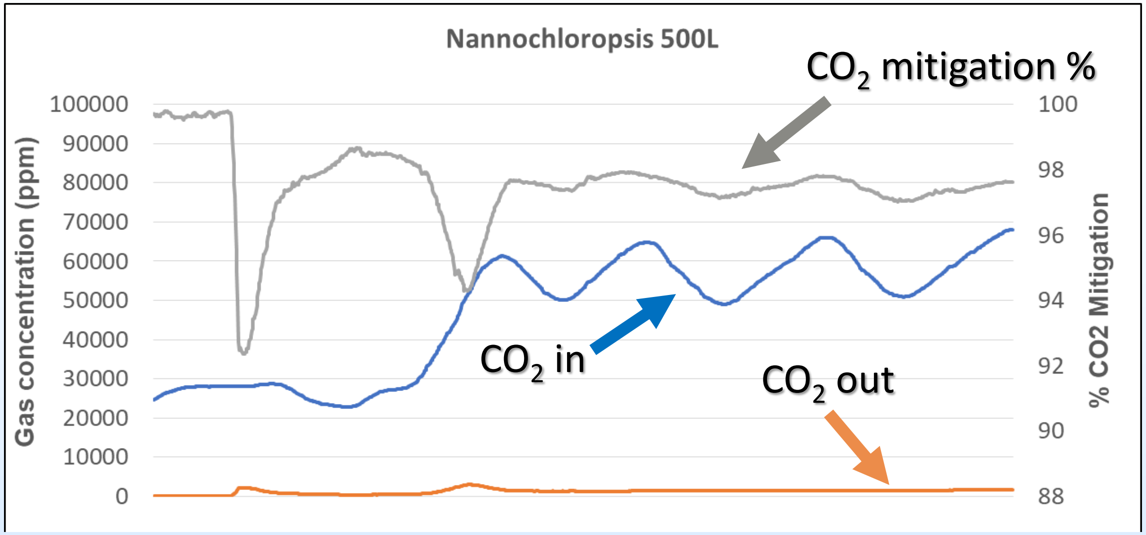
Progress- BP1 500-L scale test

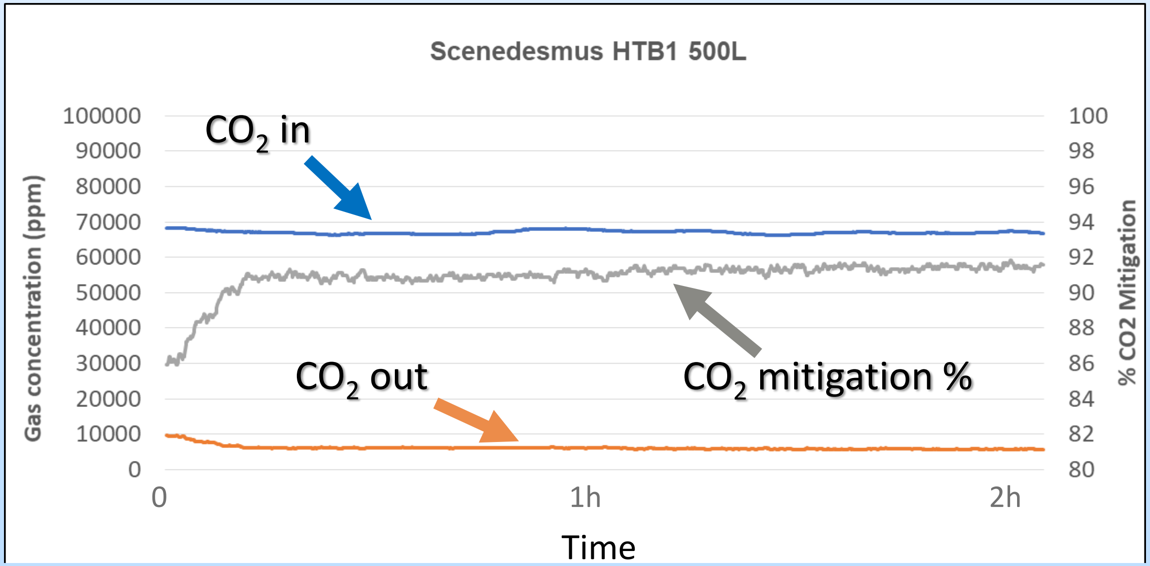
Nannochloropsis IMET1 | Scenedesmus HTB1

Nannochloropsis IMET1 | Scenedesmus HTB1

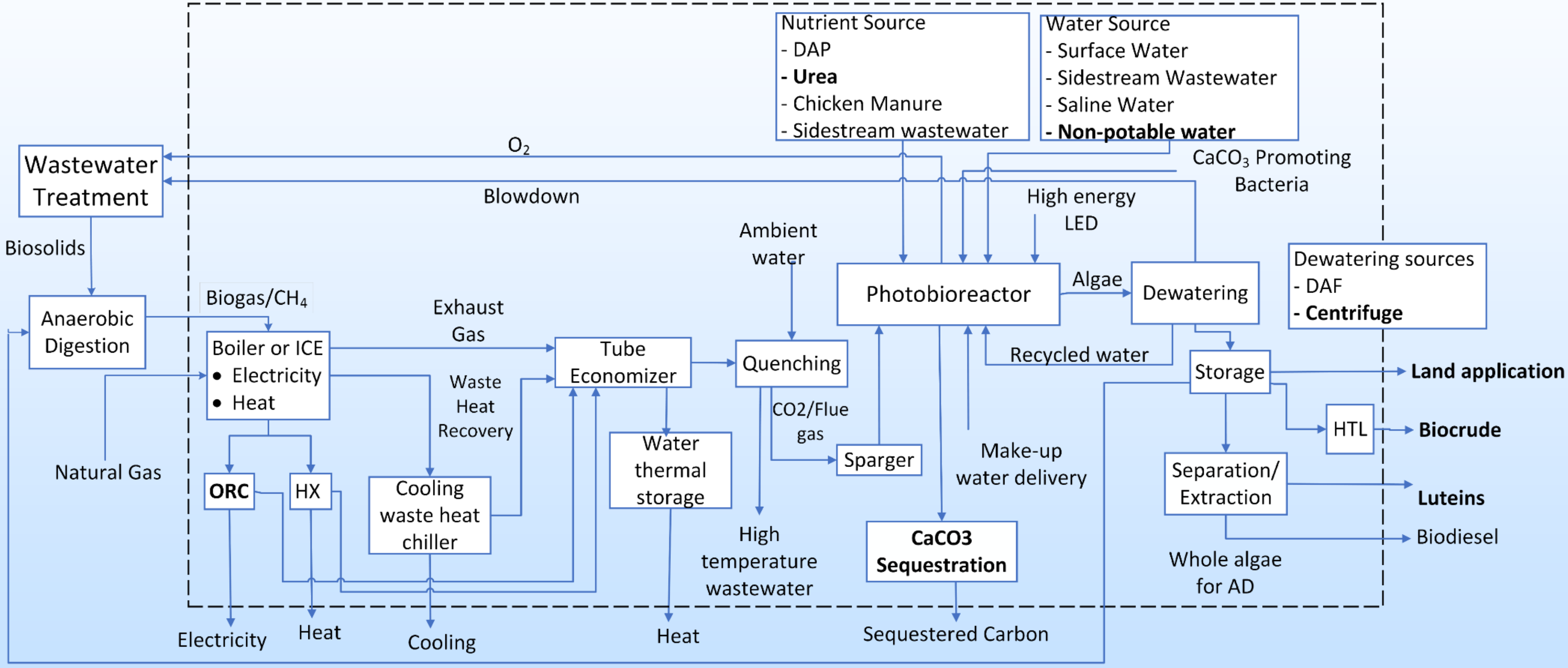


Progress- BP1 500-L scale test





Progress- BP1 LCA/TEA



Progress- Budget Period 2 (in progress 6-month NCTE)

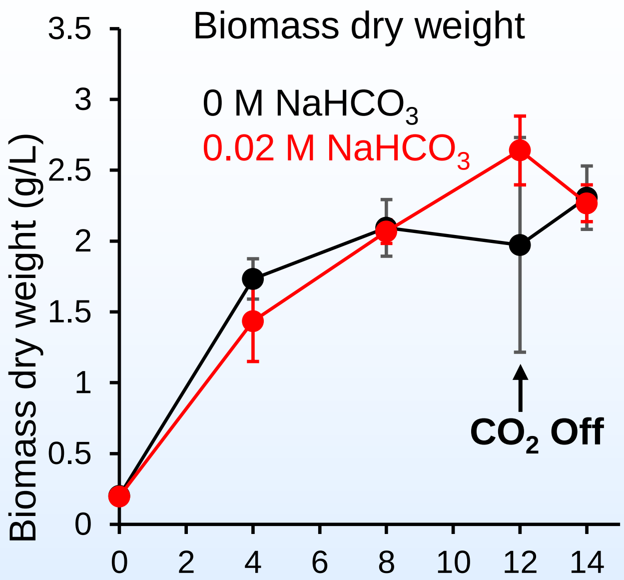
***Subtask 3.1* - Optimize algal carbon sequestration system with a marine and freshwater microalga**

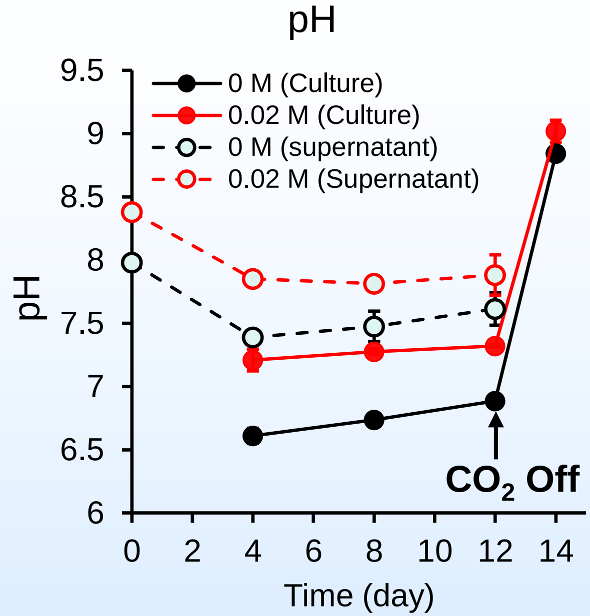
Milestone 3.1 Achieve 2 g/L biomass concentration and extra 20% carbon capture in lab cultures. M24

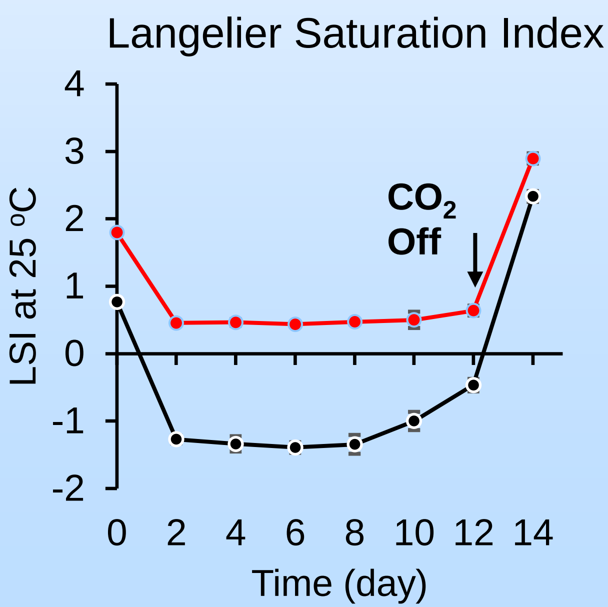
***Subtask 3.2* - Slipstream test at 500 L**

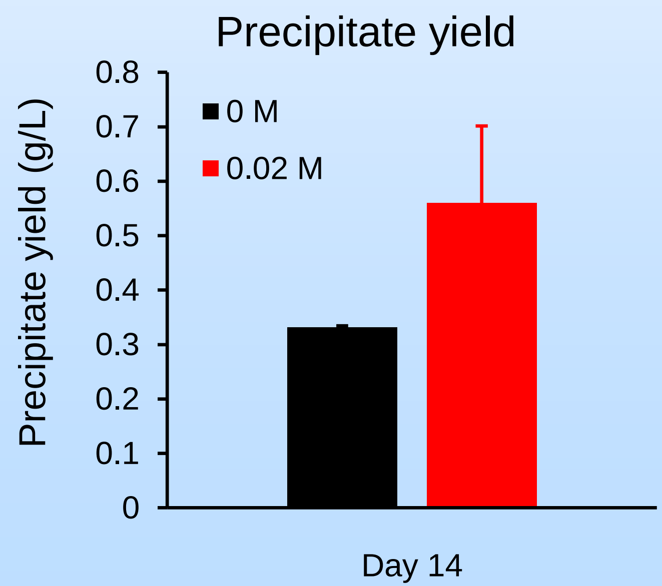
Milestone 3.2 Achieve 10-15 $g/m^2/day$ biomass productivity concentration and extra 20% carbon capture at 500 L. M30

Progress- BP 2 Lab *Nannochloropsis* culture



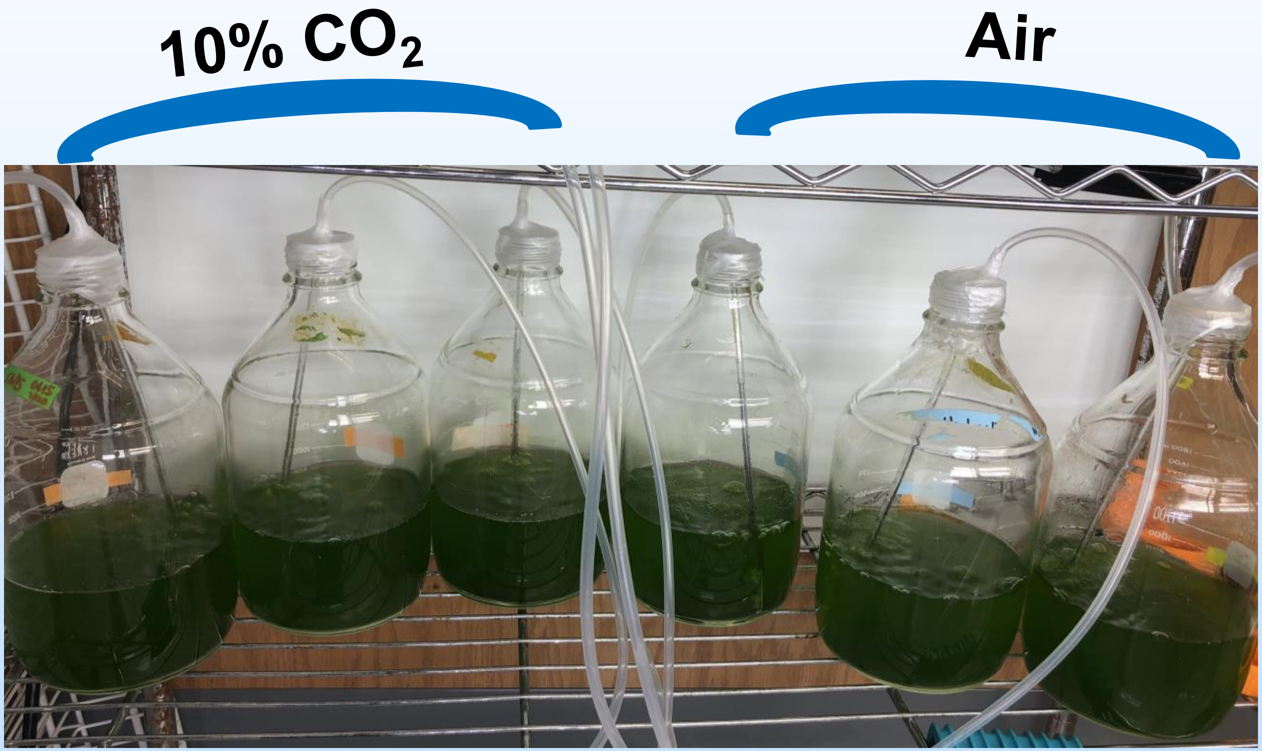






Progress- BP 2 Lab *Scenedesmus* culture

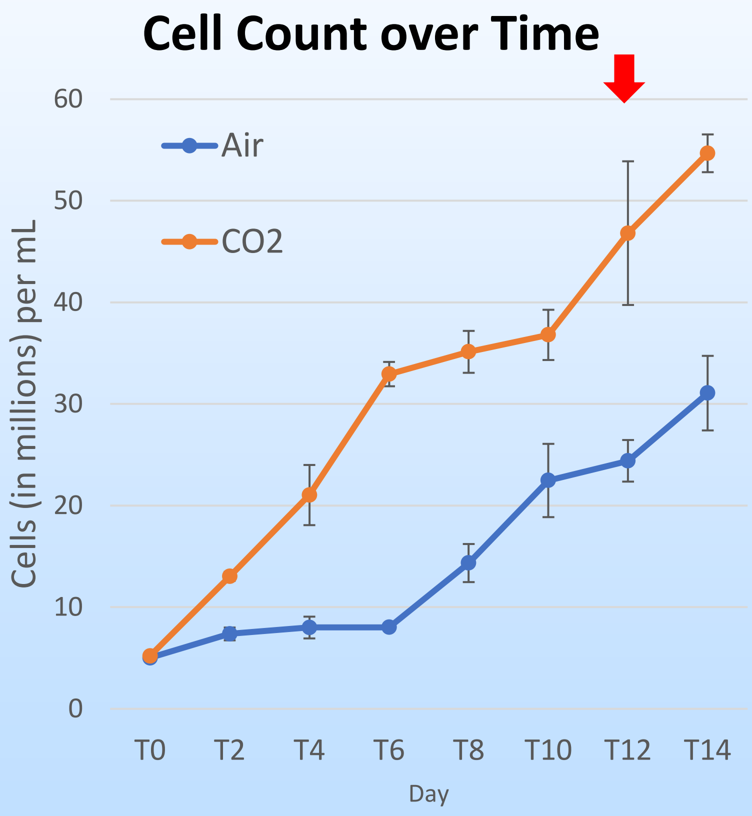
Growth of *S. obliquus* HTB1 in air and 10% CO_2

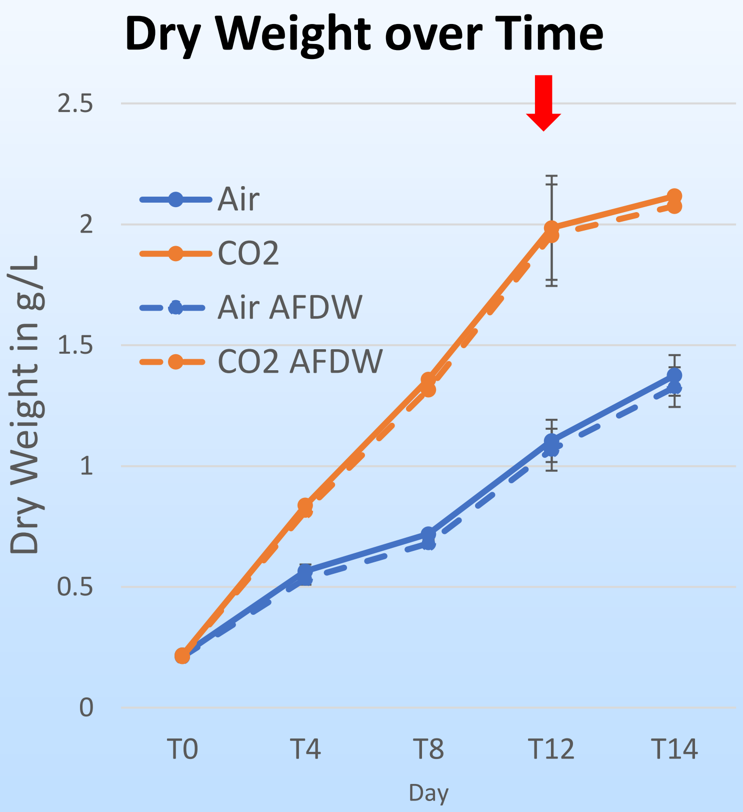


Light: 60 µmol/m2/s (day 1-11), 90 µmol/m2/s (day 11-14)
Temperature: 23-25 °C

Progress- BP 2 Lab *Scenedesmus* culture

Growth of *S. obliquus* HTB1 in air and 10% CO_2

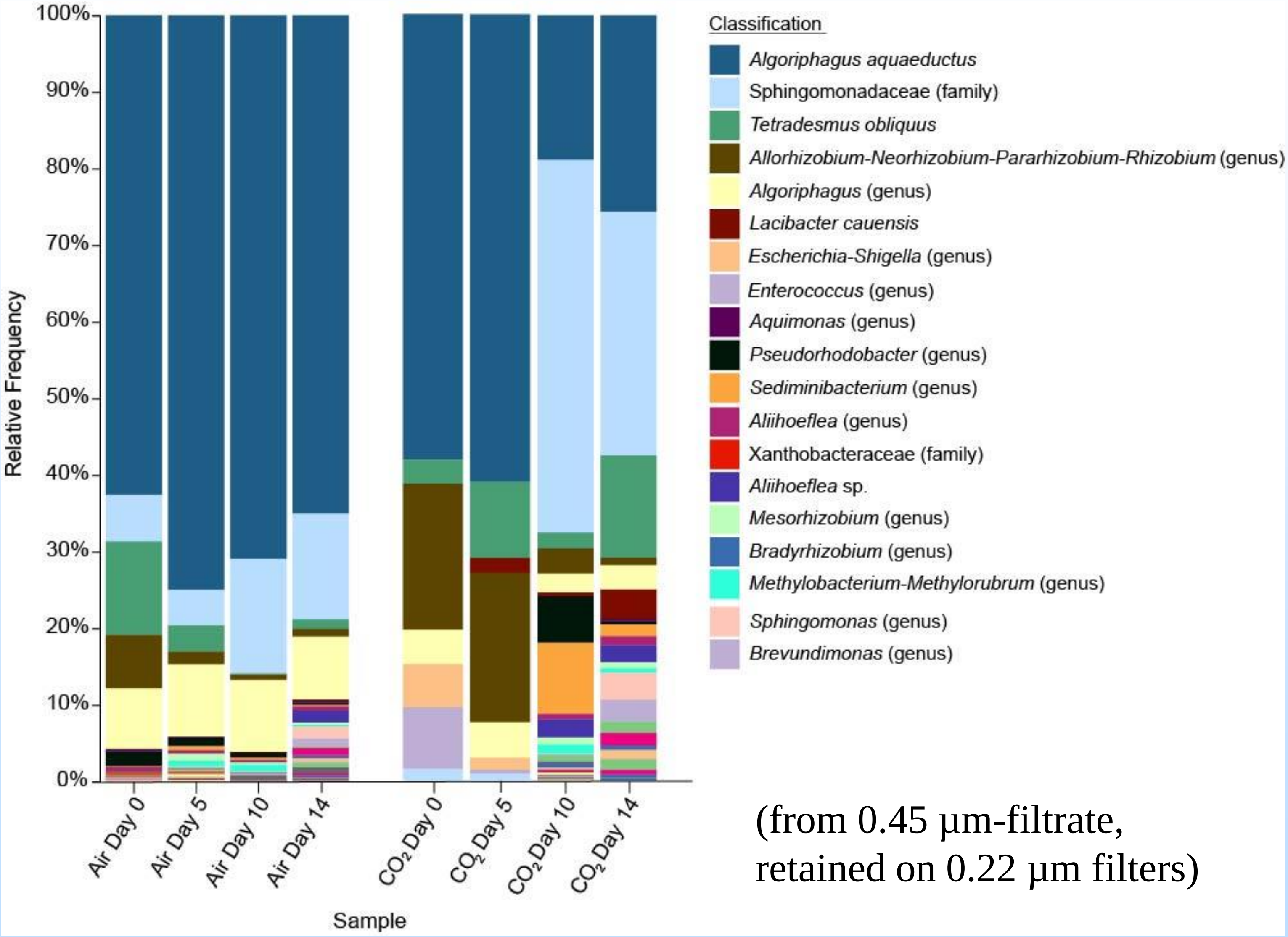




⬇ 10% CO_2 to air switch point

Progress- BP2 Lab Microbial Analysis

Free-living bacteria in *Scenedesmus* HTB1 culture



(from 0.45 µm-filtrate, retained on 0.22 µm filters)

Progress- Budget Period 2

***Subtask 3.3* – Initial slipstream testing at 6,800 L scale**

Milestone 3.3 Achieve >90% mitigation efficiency at 6,800 L. M30

***Subtask 3.4* - Use the TEA and LCA models to perform screening analysis and contribution analysis**

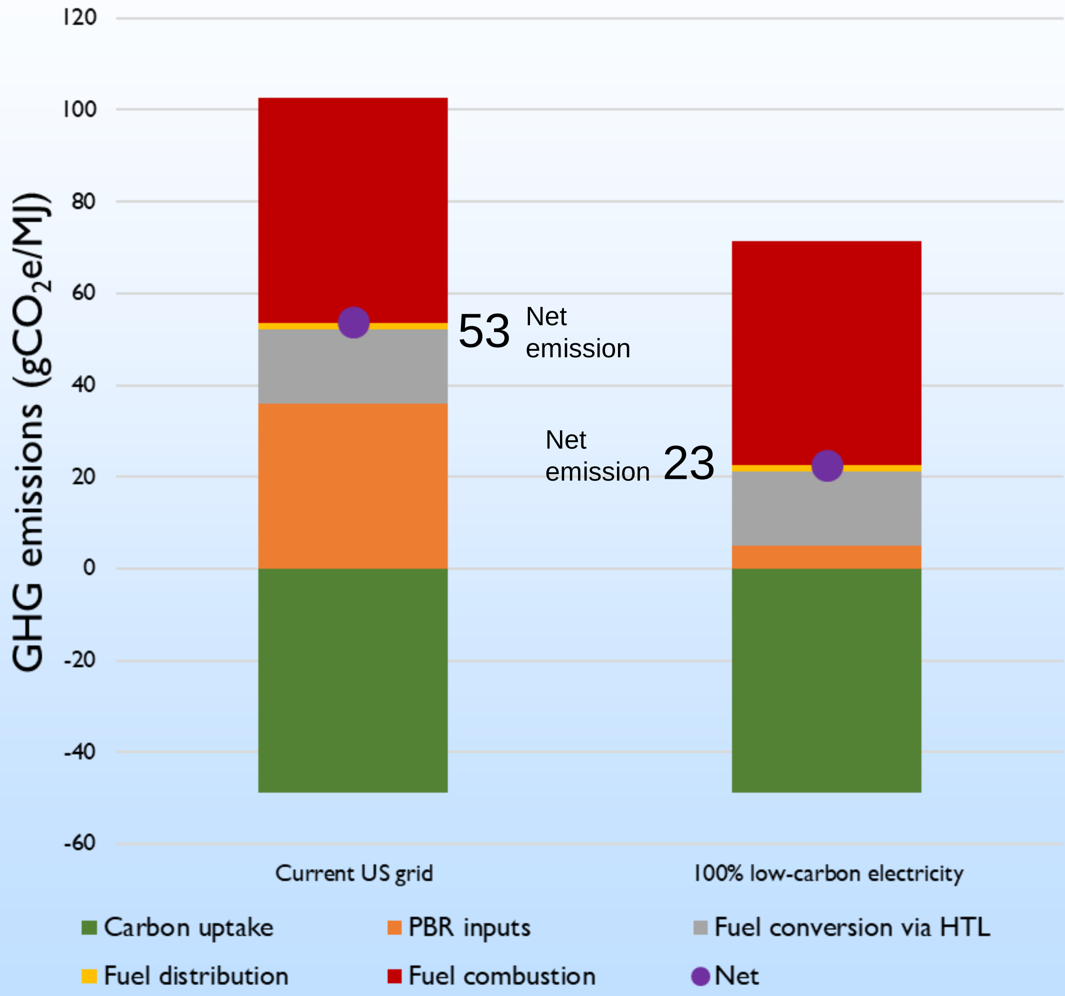
Milestone 3.4 Presentation on preliminary findings of the TEA and LCA models. M30

Progress- Budget Period 2 Slipstream test 500 L

Progress- Budget Period 2 Slipstream test 6,800 L

Looking up into a 6,800L bioreactor with 3 LED Grow Light tubes.

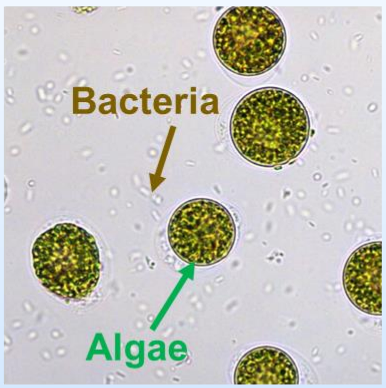
Progress- Budget Period 2 LCA/TEA



Technology Readiness Level at present

BP1

Basic principle
TRL 1



Algae-bacteria cell-cell interactions

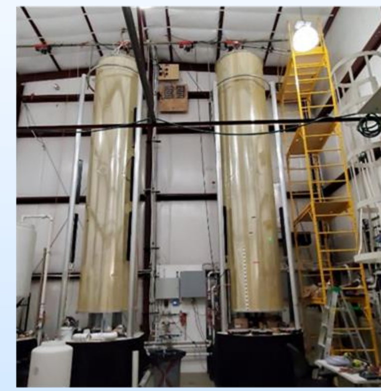
Lab scale
TRL 4

Lab-scale Reactors (1-10 L)

Pilot scale
TRL 6

Pilot-scale reactors (500 L each)

Full scale
TRL 7



Full-scale reactors (6,800 L each)

10^{-15} 10^{1} 10^{3} 10^{4} (L)

System volume

Plans for future work- BP2 and BP3

1) Bench-scale optimization of the laboratory and 500-L algal carbon sequestration system *(>20 g/m^2/Day, and extra 20-50% carbon precipitation)*;

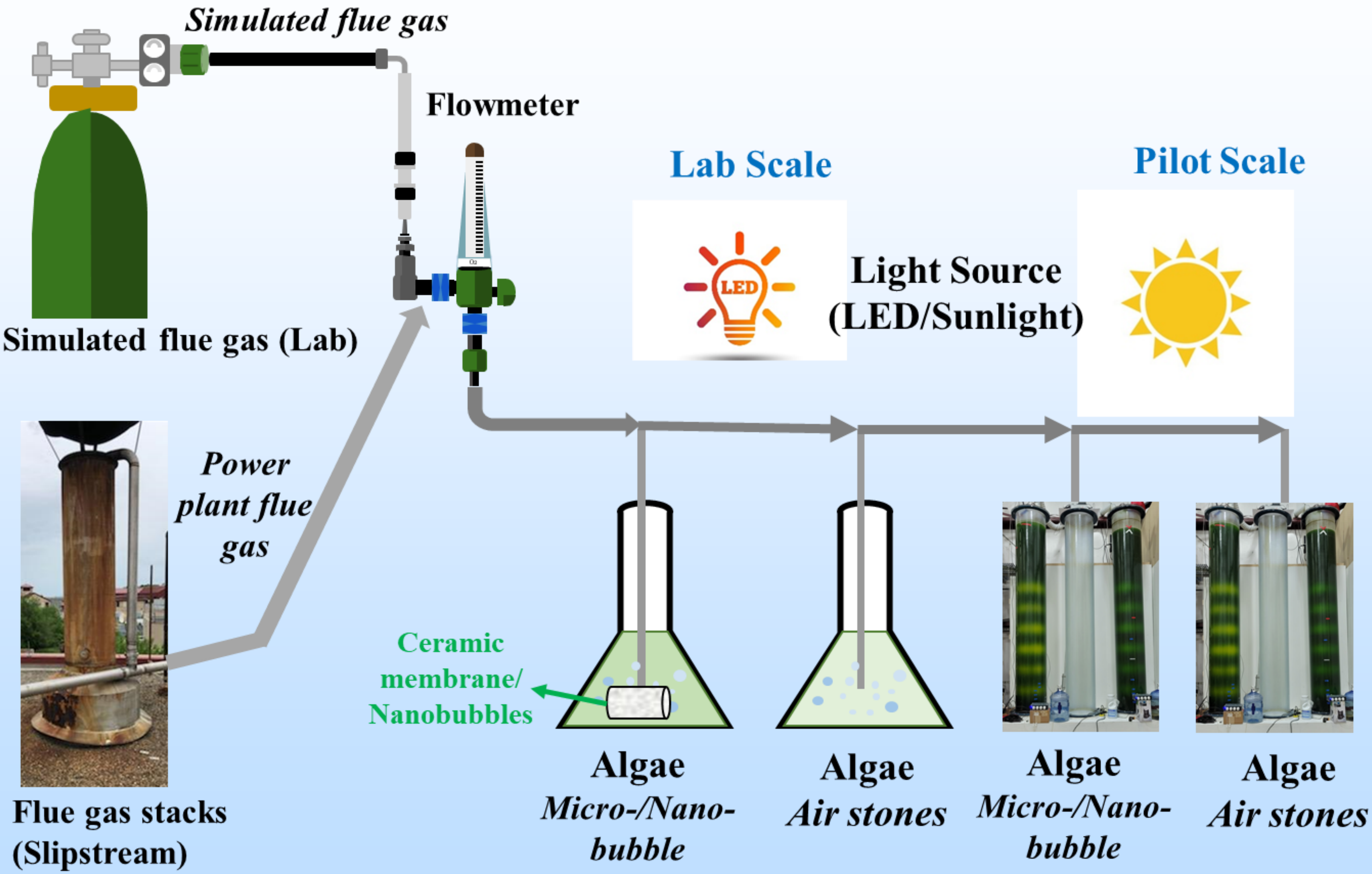
2) Use an iterative modification and validation process to scale up slipstream testing of the algal carbon sequestration system at a 6,800-L scale on power plant flue gas.

3) Perform a LCA and TEA to determine the environmental sustainability and economic viability of the proposed technology and the market penetration possibilities.

Summary

- Our freshwater *Scenedesmus* and seawater *Nannochloropsis* systems are able to capture CO_2 at >90% efficiency when grown with flue gas containing 6% or 10% CO_2.
- Algae capture CO_2 in the form of algae biomass and result in carbon precipitation. Urease-producing bacteria may help precipitate more carbon.
- Working on scaling up tests and LCA/TEA analysis. Preliminary analysis shows our technology is a promising carbon capture route.

Plans for future work: Micro-/Nano-bubbles



With Dr. Wen Zhang at NJIT

Appendix

– These slides will not be discussed during the presentation but are mandatory.

Algae

System Performance Data

	Units	Measured/Current Performance	Projected/Target Performance
Algae Characteristics			
Proposed Algae Strain	-	Nannochloropsis oceanica IMET1 and Scenedesmus HTB1	
Lower Heating Value @ 25ºC	kJ/kg (dry)	15	
Lipid Content[1]	wt%	20-51	
Protein Content	wt%	18-42	
Carbohydrate Content	wt%	8-30	
Algae Cultivation			
Method of Cultivation	-	PBR	
Water Source		Seawater for Nannochloropsis and freshwater for Scenedesmus	Seawater for Nannochloropsis and freshwater for Scenedesmus
Pond or PBR Surface Area	m2	0.19 (500 L)	1.16 (6,800 L)
Pond Depth or PBR Width	cm	290	586
PBR Type[2]	-	column airlift	column airlift
Pond or PBR Volume	L	500	6800
Nutrient Source - N	-	NO_3^- or urea	NO_3^- or urea or sterilized chicken manure
Nutrient Source - P	-	PO_4^{3-}	PO_4^{3-} or sterilized chicken manure
Scale of Operation – CO_2 delivered[3]	kg/hr	0.04	12-40
CO_2 Utilization			
CO_2 Source[4]	-	Commercial CO2 and simulated flue gas	Flue gas from power plant engine or boiler (BRWWTP)
CO_2 Content of Source Gas	mol%	6-8 (boiler) 10-12 (engine)	6-8 (boiler) 10-12 (engine)
Impurity or contaminant processing requirements[5]	-	clean source gas with no processing	clean source gas with no processing
CO_2 Processing Requirements[6]	-	no processing	no processing
CO_2 Concentration after Processing[7]	mol or wt%	6-8 (boiler) 10-12 (engine)	6-8 (boiler) 10-12 (engine)
Delivery Method to Pond/PBR[8]	-	Gas sparger	Gas sparger
CO_2 Pond/PBR Retention[9]	%	90	>90
Algae Productivity[10]			
Peak Productivity	$g/m^2/day$	20	30
Annual Average Productivity	$g/m^2/day$	15	>20
Projected Finished Products[11]		(*Market Value*)	(*Market Size*)
Product #1: Biodiesel	-	$3/gallon	$100 B
Product #2: lutein and zeaxanthin	-	$2,000/kg	$275 M

Organization Chart

No.	/Tasks	/Subtasks and PIs responsible for the task	Teams responsible
1	Project Management and Planning	• Project Management Plan ***(All PIs)*** • Technology Maturation Plan ***(All PIs)***	UMCES is the lead on this task.
2	Bench-scale development of a saltwater and a freshwater system	• Saltwater algal carbon sequestration system ***(Li and Hill, UMCES)*** • Freshwater algal carbon sequestration ***(Chen and Hill, UMCES)***	UMCES is the lead on this task.
3	Slipstream testing of the algal carbon sequestration system	• Slipstream test at 500 L scale ***(Mroz, HY-TEK Bio, LLC)*** • Slipstream test at 6,800 L scale ***(Mroz, HY-TEK Bio, LLC)***	HY-TEK Bio, LLC is the lead on this task.
4	Development of TEA and LCA models to evaluate and guide research and testing activities.	• Develop the frameworks for the TEA and LCA models (***Hawkins and Banerjee, Argonne National Lab)*** • Perform hotspot analysis, benchmark against other carbon capture and biofuel processes, (***Hawkins and Banerjee, Argonne National Lab)***	Argonne National lab is the lead on this task.

Gantt Chart

Task	2020-2021					2021-2023					2023	
Budget period	**BP 1** (Month 1-15)					**BP 2** (M 16-30)					**BP3** (M 31-36)	
Task 1.0 Project Management												
1.1 Project Management Plan												
Milestones 1.1.1												
1.2 Tech Maturation Plan												
Milestones 1.2.1												
Task 2.0 Bench-scale development												
2.1 Seawater system												
Milestones 2.1.1												
2.2 Freshwater system												
Milestones 2.2.1												
2.3 Initial 500-L test												
Milestones 2.3.1												
2.4 Frameworks of TEA and LCA												
Milestones 2.4.1												
Task 3.0 Optimization and slipstream test												
3.1 Lab-scale optimization												
Milestones 3.1.1												
3.2 Slipstream test at 500 L												
Milestones 3.2.1												
3.3 Initial 6,800-L test												
Milestones 3.3.1												
3.4 TEA and LCA analysis												
Milestones 3.4.1												
Milestones 3.4.2												
Task 4.0 Optimization and full-scale test												
4.1 Lab-scale optimization												
Milestones 4.1.1												
Milestones 4.1.2												
4.2 Slipstream test at 500 L												
Milestones 4.2.1												
4.3 Slipstream test at 6,800-L												
Milestones 4.3.1												
4.4 Frameworks of TEA and LCA												
Milestones 4.4.1												

★ Milestone ★ Go-No Go

Flow rate data

	Units	Measured/Current Performance	Projected/Target Performance
Materials Properties		(as applicable)	
Materials of Fabrication for Selective Layer		Sintered Stainless-Steel	
Materials of Fabrication for Support Layer		Sintered Stainless-Steel	
Nominal Thickness of Selective Layer	µm	3,000	3,000
Membrane Geometry[1]	-	Sintered Stainless-Steel	Sintered Stainless-Steel
Max Trans-membrane Pressure	bar	0.35	0.35
Hours tested without significant degradation		>1000	>1000
Contactor Design			
Type of Contactor	-	Gas/Liquid	
Flow Arrangement[2]	-	Full-floor	Full-floor
Packing Density[3]	m^2/m^3	NA	NA
Shell-side Fluid[4]	-	algae culture	algae culture
Contactor Performance			
Temperature	^oC	15-42	15-42
Normalized CO_2 Flux	$kgmol/m^2$-s	15 scfm (500L reactor)	100 scfm (6800 L reactor)
Type of Driving Force[5]	-	Liquid Ring Compressor	
Driving Force[6] - high potential	Bar	0.65 Bar	0.70 Bar
Driving Force - low potential	"	0.25 Bar	1.2 Bar
Delta Driving Force	"	0.08 Bar	0.14 Bar
CO_2 Selectivity[7]	mol/mol	NA	NA