Improving the Economic Viability of Biological CO_2 Utilization by Improved Algae Productivity & Integration with Wastewater Treatment

Award No: DE-FE0030822

Kickoff Meeting- Nov. 16, 2017

NATIONAL ENERGY TECHNOLOGY LABORATORY

Illinois Sustainable Technology Center | ILLINOIS

Helios-NRG, LLC

Basic Project Information

- Title: *Improving the Economic Viability of Biological Utilization of Coal Power Plant CO_2 by Improved Algae Productivity & Integration w/ Wastewater Treatment*
  - Lead Organization: University of Illinois at Urbana-Champaign
  - PI: Lance Schideman, PhD, PE
  - Collaborating Organization: Helios-NRG
  - Project Award Number: DE-FE0030822
- **DOE Funding Program DE-FOA-0001622:** ***Applications for Technologies Directed at Utilizing Carbon Dioxide from Coal Fired Power Plants***
  - Total Project Value: $1,249,873 Government : $999,536 Cost Share: $250,337
  - BP1 Total Value: $ 414,242 Government : $331,394 Cost Share: $ 82,848
- **Project Period: October 1, 2017 – September 30, 2020 with Annual Budget Periods**
  - Budget Period 1- October 1, 2017 – September 30, 2018

Organizational Chart

- **Industrial Advisory Board**
  - Springfield City Water, Power & Light
    - 578 MW coal-fired steam turbine generators
    - 46 MGD Drinking Water Plant
    - 2 Industrial Wastewater Plants
  - Urbana-Champaign Sanitary District
    - 40 MGD Wastewater Treatment Plant Capacity
    - 27 pump stations and sewer collection systems
  - Fehr-Graham Engineering
    - Wastewater Design Consultant

PRIME CONTRACTOR
University of Illinois (UI)

Key Personnel:

- Lance Schideman, Ph.D. (PI)
- Kevin O'Brien, Ph.D.
- Nandakishore Rajagopalan, Ph.D.
- Joshua McCann, Ph.D.

Responsibilities:

- Project Management
- HTL Process improvements
- Algae biomass characterization,
- Testing for animal feed applications
- Evaluation of sewer system for flue gas transport
- Techno-economic and Life-cycle analysis for dewatering and conversion processes

INDUSTRIAL ADVISORY BOARD
Managers and Design Consultants from Power and Wastewater Industries

Responsibilities:

- Advise on current industry drivers and concerns
- Review plans for integration with existing infrastructure facilities
- Review and comment on project results

SUBAWARDEE
Helios-NRG, LLC

Key Personnel:

- Ravi Prasad, Ph.D.
- James Maloney
- Frederick Harrington, Ph.D.

Responsibilities:

- Algae cultivation with flue gas
- Algae cultivation with wastewater
- Commercialization Strategy
- Techno-economic and Life-cycle analysis for algae cultivation and harvesting processes

Project Objectives

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- ***Improve Algae Productivity & CO_2 Capture by Improved Bioreactor Design/Oper.***
  - Multi-stage continuous reactor using simulated flue gas with key contaminants added
    - 35 $g/m^2 \cdot day$ three-season average biomass productivity by end of project
    - 70% carbon capture efficiency by end of project
- ***Improve Net Costs and Energy Inputs of Producing Algal Products***
  - Negative-cost wastewater nutrient inputs
  - Low-energy forward osmosis dewatering
  - Algal biomass for animal feed
  - Membrane separation and recycle of hydrothermal liquefaction aqueous products
  - Sanitary sewer distribution of flue gas
- ***Evaluate Life-cycle and Techno-economic Impacts of Proposed System***

Project Tasks

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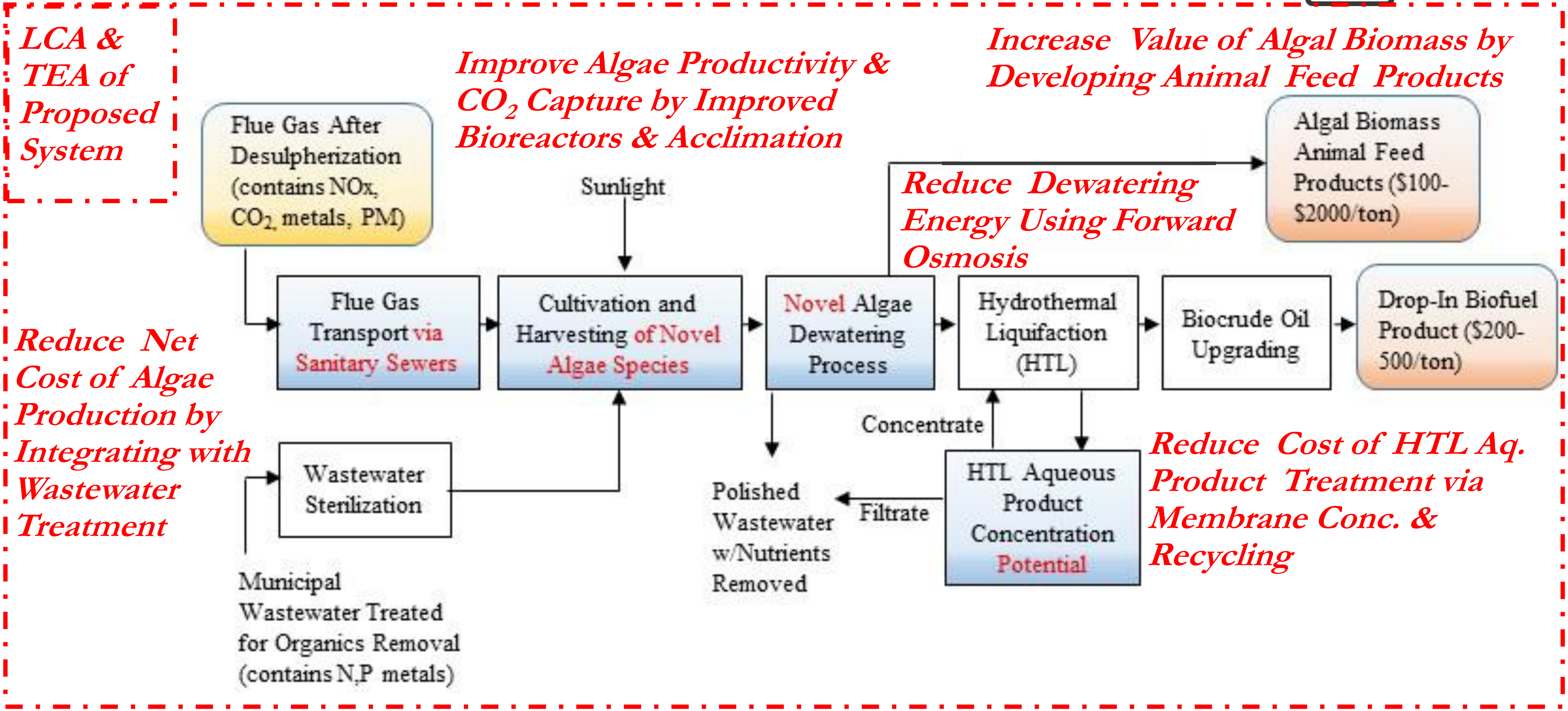
- *Task 1- Project Management*
- *Task 2- Demonstrate Stable Algae Cultivation w/ Simulated Flue Gas*
- *Task 3- Demonstrate Stable Algae Cultivation w/ Wastewater Nutrient Inputs and Simulated Flue Gas*
- *Task 4- Optimize CO_2 Capture Efficiency in the Algae Cultivation Process*
- *Task 5- Evaluate Novel Algae Dewatering Processes*
- *Task 6- Characterize algal biomass for HTL and animal feed applications*
- *Task 7- Demonstrate ability to concentrate & recycle HTL aqueous phase*
- *Task 8- Evaluate the potential of sewer network flue gas distribution*
- *Tasks 9 & 10- Techno-Economic Analysis & Life-Cycle Assessment*

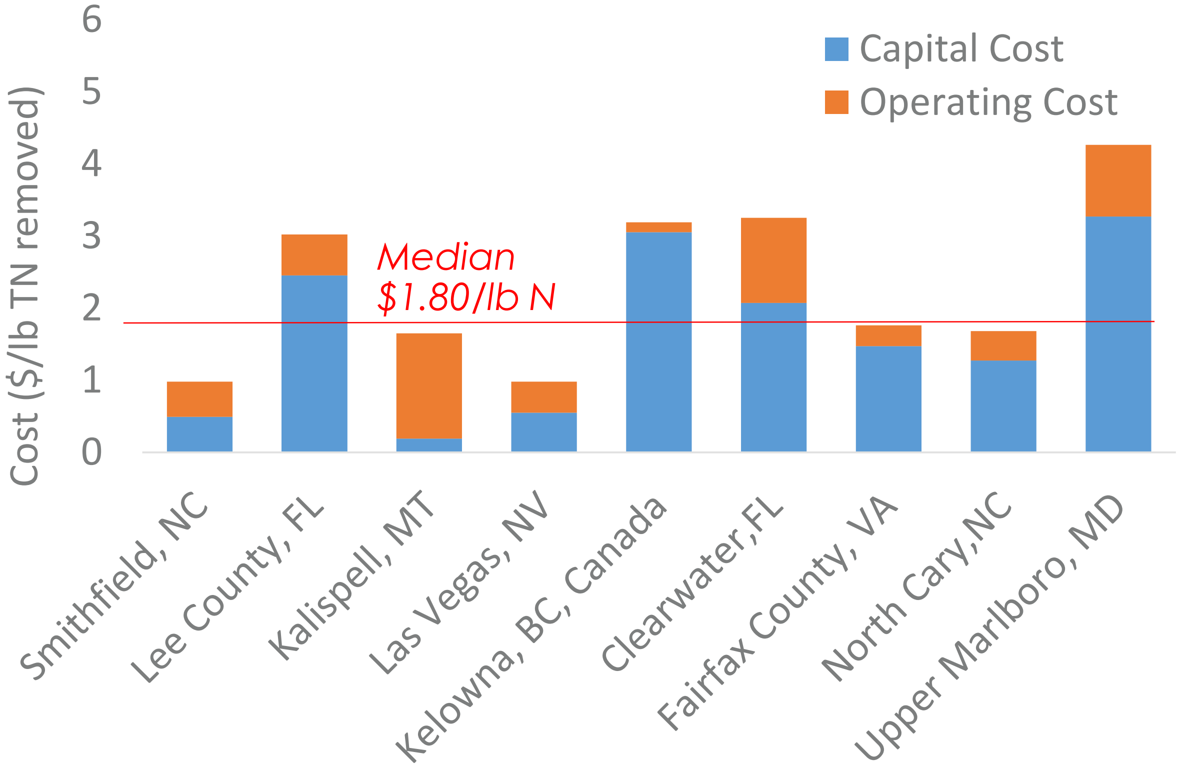
Objectives in Context of Block Flow Diagram

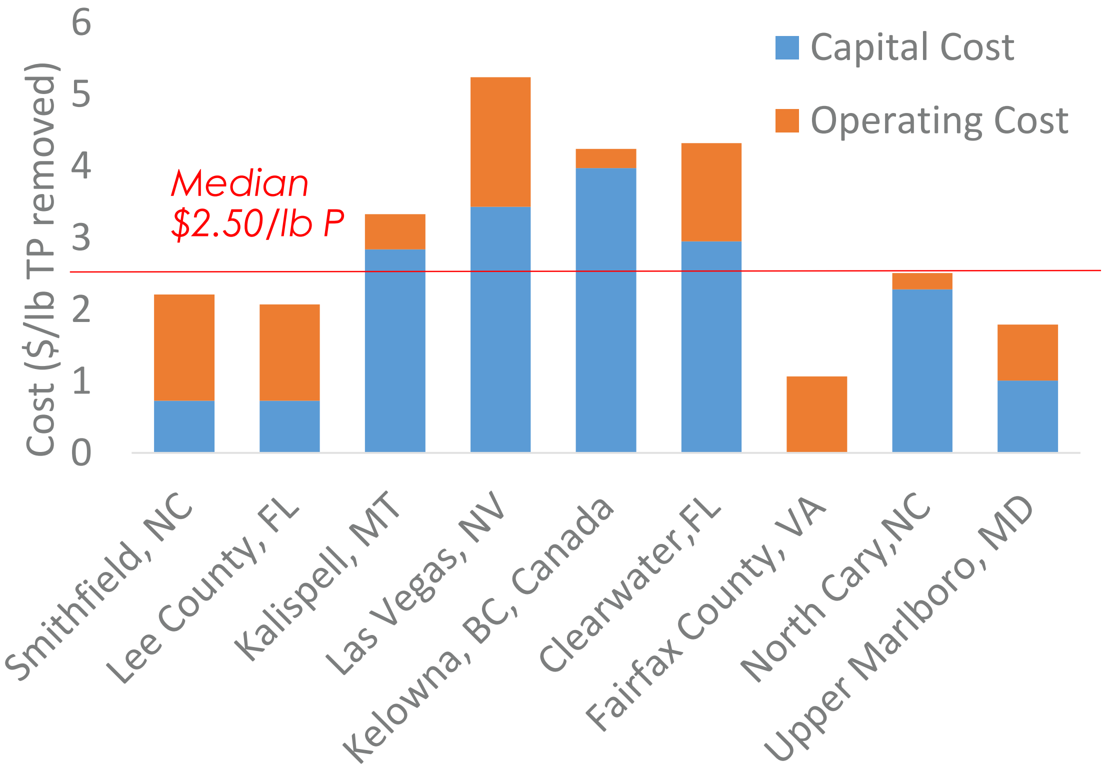


Project Rationale: *Algal biofuels can provide a large-scale beneficial reuse of flue gas CO_2, BUT lower projected costs are needed for economic viability*

Cost Categories	2015 Current State of Technology w/ Algae Productivity of 8.5 g/m²/day	2022 DOE Projected Design Case w/ Algae Productivity of 25 g/m²/day	
Algal Biomass Production Costs ($/ton)			(Proposed Project Changes)
Ponds & Inoculum	$ 1,359	$ 289	(Raceway pond mods + $44)
CO_2 Supply	$ 99	$ 97	(Carbon capture credit - $60)
Dewatering Operations	$ 82	$ 52	(Low energy FO dewatering $0)
Nutrient Supply	$ 25	$ 24	(WW trtmt. credit - $270)
Other Costs	$ 76	$ 32	
TOTAL Algae Biomass Prod	**$ 1,641 /dry ton**	**$ 494 /dry ton**	**($208/ dry ton)**
Algal Biofuel Production Costs ($/gge)			
Algae Biomass Supply	$ 15.15	$ 3.18	(Sum above methods $1.32)
Hydrothermal Liquefaction Conv.	$ 1.18	$ 0.49	
Bio-oil Upgradation/Finishing	$ 0.44	$ 0.31	
Aqueous product post-treatment	$ 1.54	$ 0.57	(Conc/recycle aq prod. $0.28)
Balance of Plant	$ 0.29	$ 0.17	
TOTAL Biofuel Cost Before Credits	$ 18.60 / gge	$ 4.72/gge	**($2.58/ gge)**

Typical Wastewater Nutrient Removal Costs

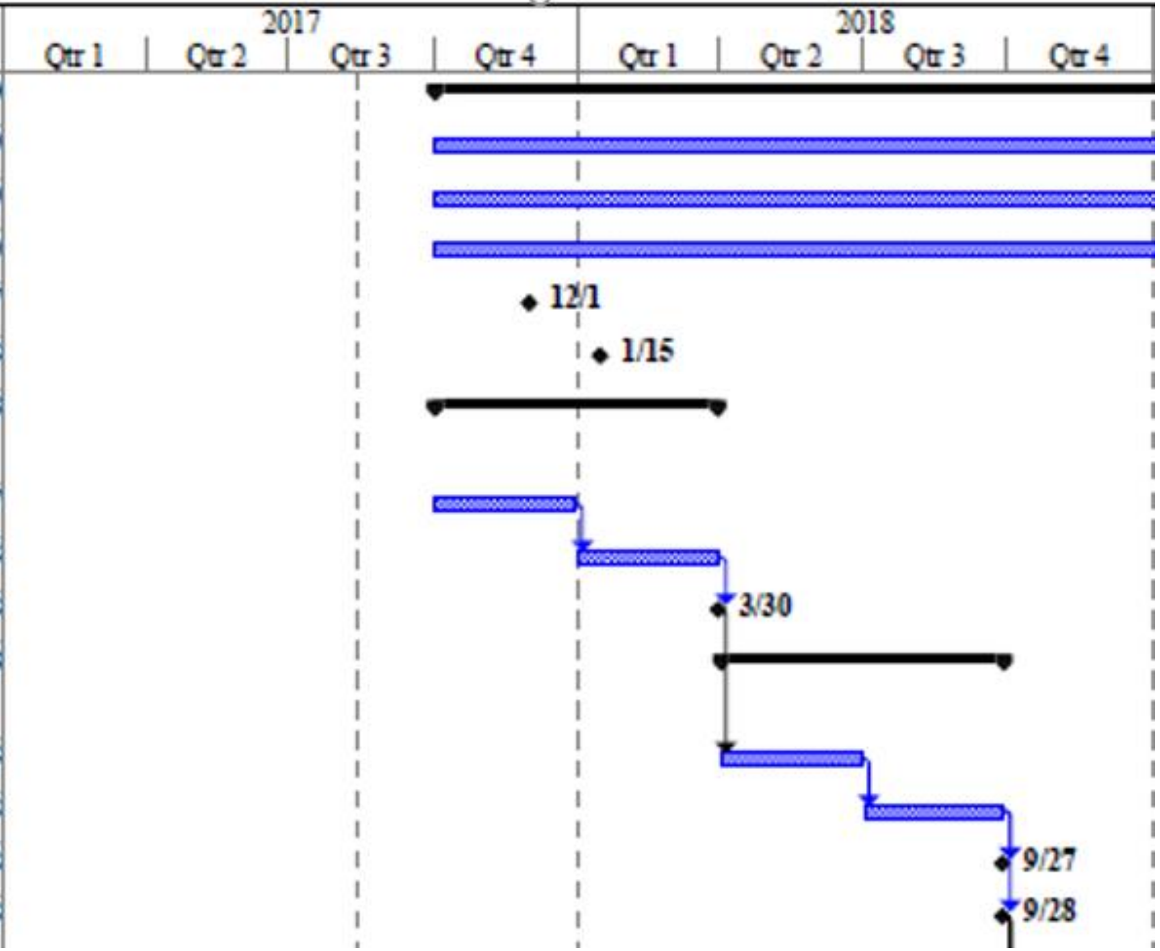




- **Baseline Algae Elemental Mass Composition- 36%C, 7%H, 50%O, 6%N, 1%P**
- **Wastewater Treatment Value of Algal Nutrient Uptake = 2000*(0.06*$1.80+0.01*2.50) = $266/ton algae**

Project Schedule for Budget Period 1

Task Name	Start	Finish
1.0 Project Management Plan	**Mon 10/2/17**	**Wed 9/30/20**
1.1 Monitoring and Control	Mon 10/2/17	Wed 9/30/20
1.2 Briefings and Reports	Mon 10/2/17	Wed 9/30/20
1.3 Meetings and Conferences	Mon 10/2/17	Wed 9/30/20
Updated Project Management Plan	Fri 12/1/17	Fri 12/1/17
Kickoff Meeting	Mon 1/15/18	Mon 1/15/18
2.0 Demonstrate Stable Productivity of Algal CO2 Utilization System with Simulated Coal Flue Gas	**Mon 10/2/17**	**Fri 3/30/18**
2.1 Demonstrate Performance with Major Flue Gas Constituents	Mon 10/2/17	Fri 12/29/17
2.2 Demonstrate Performance with Minor Flue Gas Constituents	Mon 1/1/18	Fri 3/30/18
Stable Algae Growth w/ Nox, Sox Added to Simulated Flue Gas	Fri 3/30/18	Fri 3/30/18
3.0 Demonstrate Stable Productivity of Algal CO2 Utilization System w/ Wastewater Nutrients & Simulated Coal Flue Gas	**Mon 4/2/18**	**Fri 9/28/18**
3.1 Demonstrate Performance with Macro-Nutrients from Wastewater	Mon 4/2/18	Fri 6/29/18
3.2 Demonstrate Performance with Micro-Nutrients from Wastewater	Mon 7/2/18	Thu 9/27/18
Stable Algae Growth w/ Heavy Metals Added to Simulated Flue Gas	Thu 9/27/18	Thu 9/27/18
GO/NO-GO Decision: Algal Productivity Above DOE Baseline State of Technology	Fri 9/28/18	Fri 9/28/18



Project Milestones for Budget Period 1

Table 1. Milestone Log

Budget Period	Task #	Mile-stone #	Description	Planned Completion Date	Actual Completion Date	Verification Method
1	1	T1.1	Kickoff Meeting	Month 2		Presentation file
1	1	T1.2	Updated Project Management Plan	Month 3		Project Management Plan File
1	2	T2.1	Stable Algae Growth with simulated flue gas	Month 6		Topical Progress Report
1	3	T3.1	Stable Algae Growth with wastewater nutrients	Month 12		Budget Period 1 Progress Report
1		G/N-1	Algal Productivity with Simulated Flue Gas > 25 $g/m^2/d$	Month 12		DOE Annual Review

Technical Risks & Mitigation

Description of Risk	Probability	Impact	Risk Management- Mitigation and Response Strategies
Technical Risks:			
Algae growth is inhibited by contaminants in post-FGD flue gas (SO_x, NO_x, metals)	Medium	Medium to High	• Provide adsorbents to sequester problem contaminants • Problem contaminants can be removed from the simulated flue gas • For future applications flue gas pre-treatment would be required
Algae growth is inhibited by contaminants in nutrient-rich wastewater filtrate liquids	Low	Medium to High	• Provide adsorbents to sequester problem contaminants • Wastewater filtrate can be pre-treated to remove problem contam. • Wastewater filtrate use for algae cultivation can reduced/eliminated
Algal uptake of CO_2 is not fast enough for capture goal (70-90% removal in 3 stages)	Low	Low	• Provide fine bubble diffusers if it is a physical mass transfer limitation • Add stages if it is a biological limitation
Forward osmosis dewatering flux is too low to facilitate cost-effective applications	Low	Medium	• Pre-treat algal biomass with ultrasound to open cells and reduce resistance to water diffusion through the cell walls • Use alternate dewatering methods
Concentrated HTL aqueous product is not converted to bio-oil when recycled	Low	Low	• Use alternate methods for treatment of HTL aqueous product (anaerobic digestion, or catalytic hydrothermal gasification)
Sewer conveyance of flue gas causes too much loss/dilution	Medium	Low	• Use a dedicated pipeline for transport of CO_2 from flue gas

Project Activities To Date

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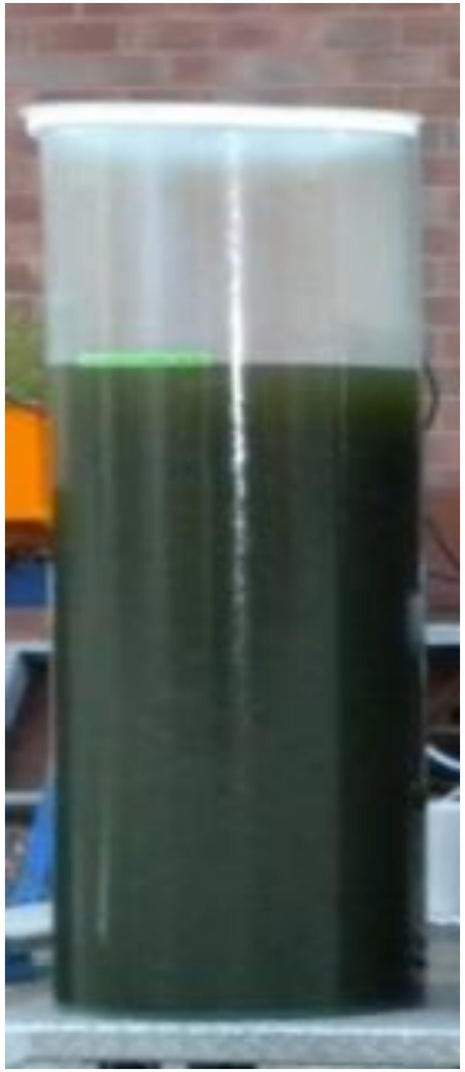
- Prime Contracting with University Illinois
- Sub-Contracting with Helios-NRG
- Industrial Advisory Board Member Confirmation
- Initiated Task 2- Algae Cultivation w/ Simulated Flue Gas & Contaminants

Technology Description & Background Work



General Strategy for Algal CO_2 Capture

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- Utilize micro-algae to metabolize and capture CO_2
- Design process to enable high CO_2 capture efficiency
- De-water the algae at low energy & cost
- Recycle water & nutrients to minimize consumption
- Utilize algae to make products to reduce capture costs
  - Bio fuel via HTL process
  - Higher value co-products – animal feed, nutraceuticals

Challenges in Algae CO_2 Capture

- **Algae is a living thing – complex & prediction difficult**
  - Control of contamination is essential
- **Flue gas contaminants can be harmful**
  - 12% CO_2 is 300x of ambient
  - Acid gases (SO_X, NO_X) lower pH
  - Heavy metals can be toxic
- **Typically growth rate & capture eff inversely related**
- **Photosynthesis limits capture to daylight hours**
- **All downstream applications require dewatering**

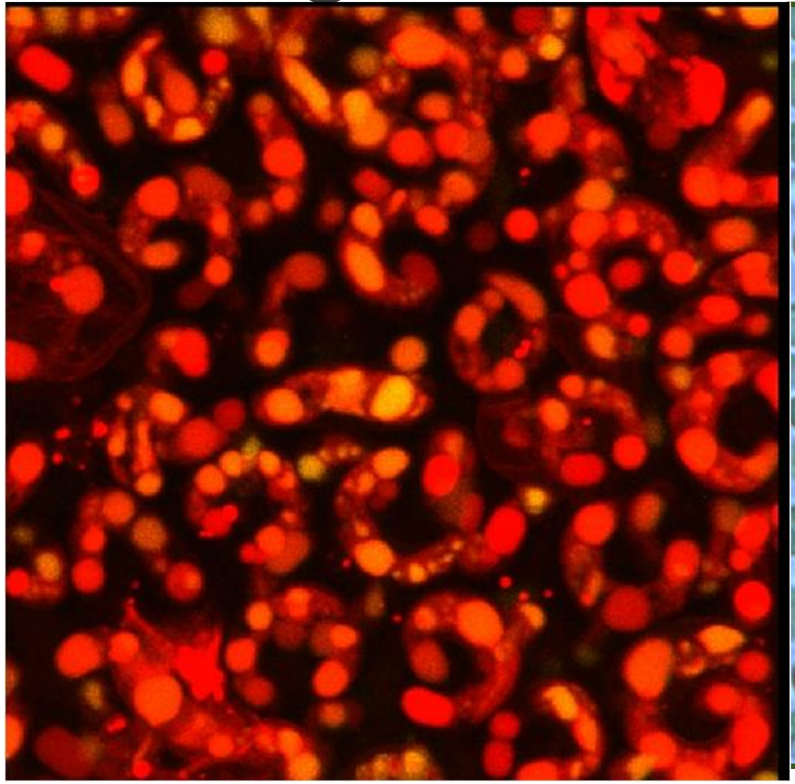
Approach to Address Challenges

- **Control of contamination: Photo-bioreactors (PBR)**
- **Flue gas contaminants: Species selection, reactor & process design**
- **High Productivity + Capture Efficiency: Multi-Stage Continuous Process (MSC)**
- **De-watering: New technology (Forward Osmosis; DeAqua)**
- **Complexity of algal system: Proprietary simulation tools developed in-house over last 7 years**

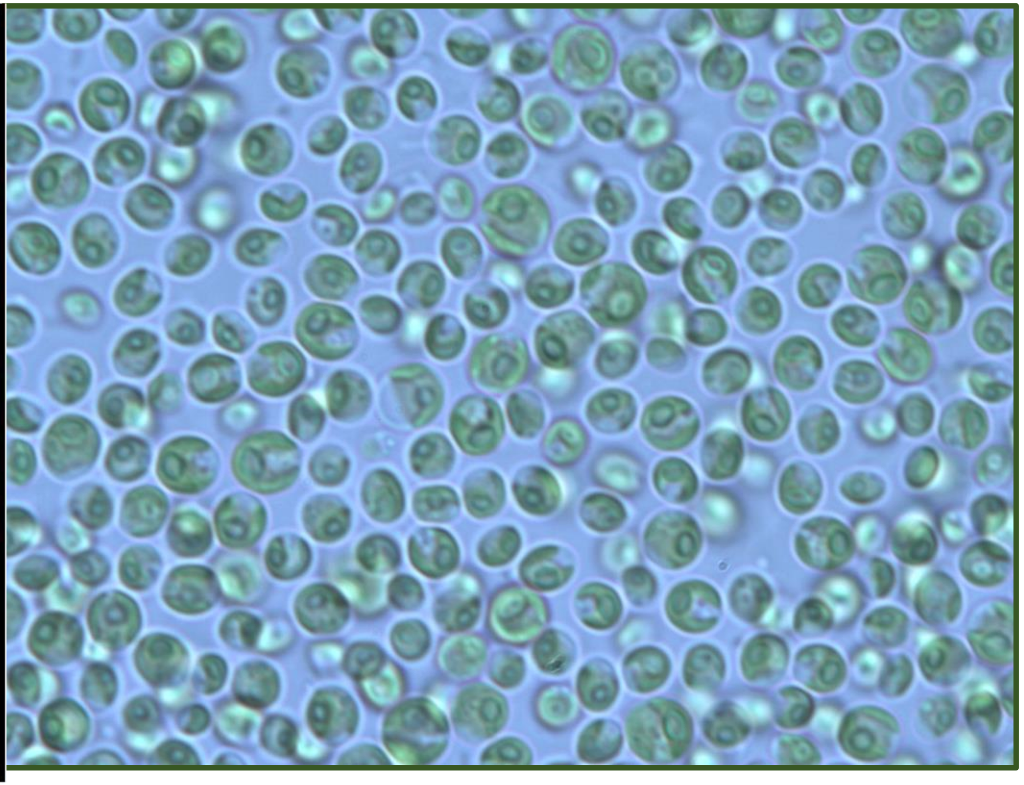
Algae Species Selection

- **Primary criteria**
  - High tolerance to flue gas contaminants
  - High growth rates
  - Only naturally occurring species – no GMO's
  - Prior Helios experience & well characterized
- **Two candidate species selected for current project**
  - Can handle 12% CO2
  - Survives SO_X & NO_X
  - Survival with Hg, As, Se previously tested

Preferred Algae Strains



H-1903



H-0322

Stable algae growth demonstrated for H-0322 and H-1903 at $12\% CO_2$ + 75ppm SOx + 75ppm NOx

Prior Work with Heavy Metals

- Several organic & inorganic species investigated to date
- Heavy Metals studied: Zn, Hg, As, Se
- Algae can uptake heavy metal from culture
- Minimal effect at low concentration
- But growth inhibited at high concentration

Benefits of Multi-Stage Continuous (MSC) Process

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- Enables stable capture efficiency over time
- Potential for 90% CO_2 capture from flue gas
- High productivity & low down time
- Suitable for integrating with upstream & downstream processes
- Easier to maintain culture health

Past Work with Hydrothermal Liquefaction (HTL)

Demonstrated HTL Feedstocks

Algae
Municipal sludge
Manure
Crop residues
Woody materials

HTL Reactor

Temp: 200 – 350 °C
Pressure : 80 – 120 atm
Reaction Time: 30-60 min

Typical Product Distr.

Product		
Gas Product	5%C	1%>N
HTL Aq. Product	20%C	70%N
Solid Residue (Char)	10%C	10%N
Oil Product	65%C	20%N

Eout : Ein > 3:1 at lab-scale (% solids =20%)
Eout : Ein > 10:1 w/ heat exchangers as estimated by commercial partners

Previous HTL Tests with Helios Algae

- **Assessed the effect of HTL operating conditions & algae type on performance**
  - Tested many different HTL operating conditions
  - Optimized process for oil yield and oil quality (HHV)
  - Characterized HTL aqueous product for recycle
- **High oil yield demonstrated for both algae species**
- **Bio-crude with good heating value produced**
- **Biochar yield as low as 15%**
- **Ability of algae to handle recycle and potential for nutrient reduction demonstrated**

HTL Aqueous Product as a High Nutrient Conc. - *but also other things*

Water Quality Parameter	Average Value	Standard Deviation
Chemical Oxygen Demand (COD), g/L	87.6	± 13.2
Ammonia Nitrogen, g/L as N	4.19	± 0.08
Total Nitrogen, g/L as N	11.5	± 0.86

Benefits of Recycling HTL Aq. Product:

1. **Reduces water & nutrient needs**
2. **Eliminates need for disposal or post-treatment**

Key Question: Can algae tolerate this HTL aqueous phase?

HTL Aquous Product Characterization

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HTL aq. product contains high conc. of organics (40-120 g COD/L) and nutrients (1-15 g/L N & P)

Characteristics of HTL Aq Product from conversion of mixed-culture algae

Classes of Molecules	GC/MS relative abundance @ various temperatures			
	260°C	280°C	300°C	320°C
Short chain organic acid (C2-C4)	21.1%	26.7%	34.6%	9.10%
Long chain organic acid (C5-C6)	1.89%	2.98%	4.26%	8.74%
Fatty acid & fatty alcohols	3.78%	7.13%	4.01%	1.78%
Amino acid	7.07%	4.91%	4.88%	0.14%
Benezoic acid derivatives	2.03%	1.38%	2.70%	5.55%
Cyclic Hydrocarbons	Nd	Nd	0.39%	Nd
Phenols	0.21%	0.36%	0.57%	8.44%
Straight amides derivatives	6.31%	5.89%	2.74%	16.3%
N-heterocyclic compounds	31.6%	31.0%	36.7%	36.8%
Oxygenates (cyclic and straight)	6.70%	10.1%	1.82%	1.48%
Ketones	11.6%	4.94%	1.83%	4.98%

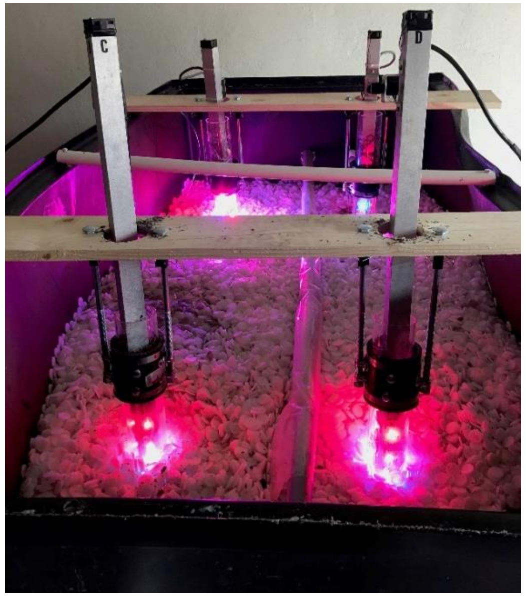
Source: Tommaso et al., 2015 Bioresource Technology 178:139-146

Survival of H-1903 algae with HTL aq. product

- Stable algae growth with HTL aqueous waste demonstrated
- Potential for nutrient reduction – not full replacement

Previous Work on Integration of WW Treatment w/ Algae Cultivation

- **Long-term study of swine wastewater treatment for USDA**
  - Good removal of ammonia & organics
  - Partial removal of total P and N
  - Good hormones & pharm. removal
  - Up to 1000 gal/day treated
- **Recent ongoing study with municipal wastewater for MWRD-Chicago**
  - 6 hr hydaulic retention time can provide ~65% P removal
  - Adding CO_2 increased biomass production and P removal ~10%
  - Planning for ~50,000 gpd pilot



Budget Period 1 Experimental Plan

Task2: Optimize algal system with simulated coal flue gas post-FGD with NO_x, SO_x, and selected heavy metals

Task3: Evaluate use of wastewater nutrients in algal system with simulated coal flue gas

Post FGD Gas Profile

- **Post FGD contains 12% CO_2, ~75ppm SO_2 and ~75ppm NO_X**
  - Simulated by adding these species to air

- **Several heavy metals present in flue gas**
  - Simulated by adding these species to liquid growth media

Typical Post FGD Flue Gas

Metals	Conc (ppb)
As	78.9
Cd	15.2
Co	16.2
Cr	131.5
Cu	132.5
Hg	10.1
Pb	54.6
Ni	252.9
Se	10.1
Zn	445.0

Source: Napan, K. "Contamination levels in biomass and spent media from algal cultivation system contaminated with heavy metals". Algal Research 19 (2016), 39-47

Testing effects of flue gas contaminants

- All tests will be on gas with 12% CO_2, ~75ppm SO_2 and ~75ppm NO_X
- Soluble salts of heavy metals added directly to culture in solution
- Two algae species will be studied – additional if needed

Potential concerns with utilizing waste-water nutrients & mitigation measures

- **Are there harmful pathogens in wastewater?**
  - **Wastewaters will be filtered and/or heat treated**
- **Are there inhibitory chemicals in the wastewater?**
  - **Adsorptive and/or membrane treatments of wastewater will be tested**
- **Are all nutrients required for algae present in wastewater?**
  - **Use variable concentrations of typical growth media and wastewater**
- **Does wastewater composition vary with time and location?**
  - **Future Work**

Questions and Comments…

Lance Schideman
schidema@Illinois.edu
www.algae.Illinois.edu

istc.illinois.edu