August 8-12, 2016 • Pittsburgh

U.S. Department of Energy, Office of Fossil Energy, NETL

DE-FE0026490, 10/01/15– 09/30/17, Andy Aurelio, P.M.,

MicroBio Engineering, Inc.,

"Microalgae Commodities from Coal Plant Flue Gas CO2"

Funding: DOE NETL: $863,327

Orlando Utilities Commission (OUC) Cost Share: $282,640

John Benemann, P.I., Tryg Lundquist, Co-P.I., Kyle Poole, Project Engineer

PROJECT PARTICIPANTS

- **MicroBio Engineering Inc. (MBE), Prime , P.I.: John Benemann, CEO**
  TEAs, LCAs, gap analyses, ponds for OUC & UF, Project management
- **Subrecipients:**
- **Orlando Utilities Commission (OUC)**: provide data on SEC power plant, emissions, etc. ; Operate test ponds at SEC with flue gas CO_2
- **Univ. of Florida (UF)**: operate test ponds, algae anaerobic digestion
- **Arizona State Univ.**: Train OUC and UF staff in algae cultivation
- **Scripps Institution of Oceanography (SIO), Lifecycle Associates (LCA), SFA Pacific Inc.**: LCA, TEA and engineering assistance to MBE

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MicroBio Engineering Inc., San Luis Obispo, California

Facilities Designs – Equipment – Wastewater Reclamation – Scientific Consulting – R&D – Life Cycle Assessments – Techno-Economic Analyses


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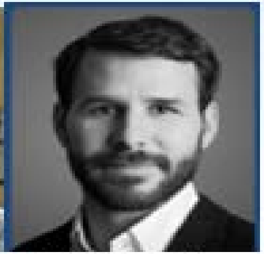

Kyle Poole

Overall Project Objectives

- **Primary Objective:** detailed site specific Techno-economic Analysis (TEA) and Life Cycle Assessment (LCAs) for the Orlando Utilities Commission Stanton energy Center OUC-SEC Coal-fired power plant for CO_2 utilization /mitigation options:

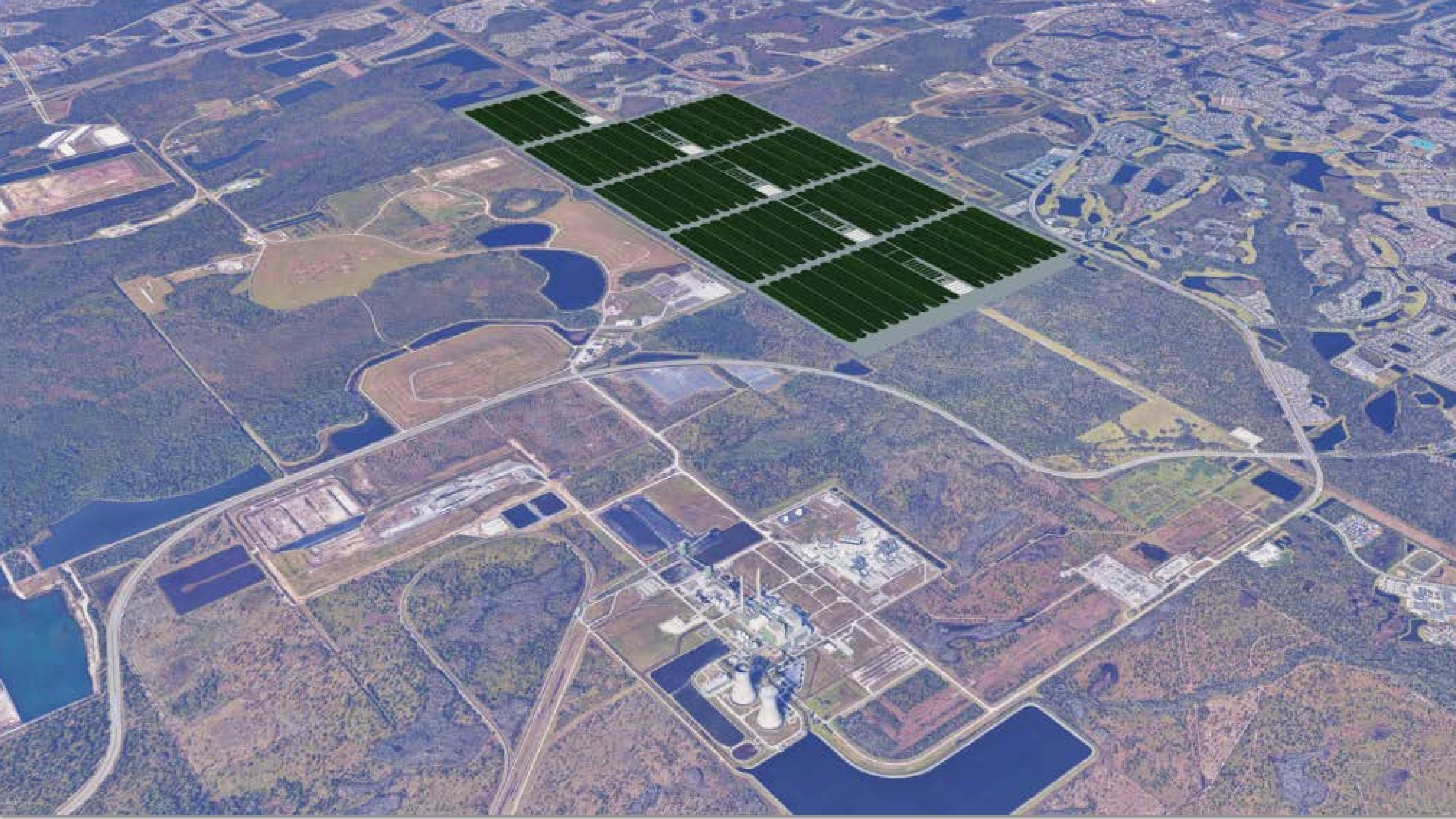
  Case 1 (Budget Period 1) Biogas production from algal biomass to replace coal for maximum CO_2 mitigation (Budget Period 1), and

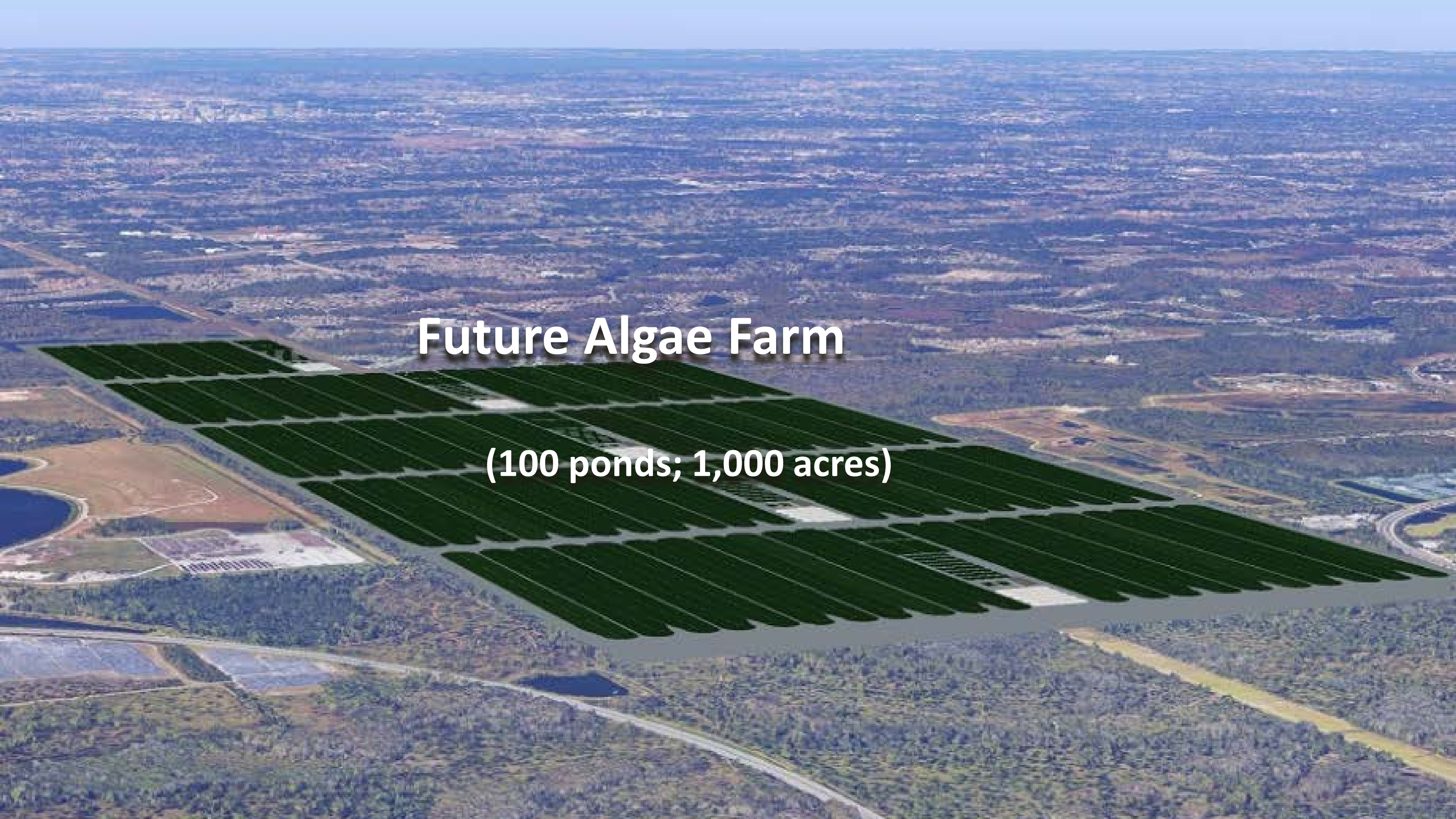
  Case 2 Production of commodity microalgae animal feeds, for maximum beneficial economic use of flue gas CO_2 (BP2)

- **Secondary Objective**: experimental work at OUC-SEC and UF to demonstrate algae biomass production using flue gas CO2 with native algae and conversion to biogas and animal feeds

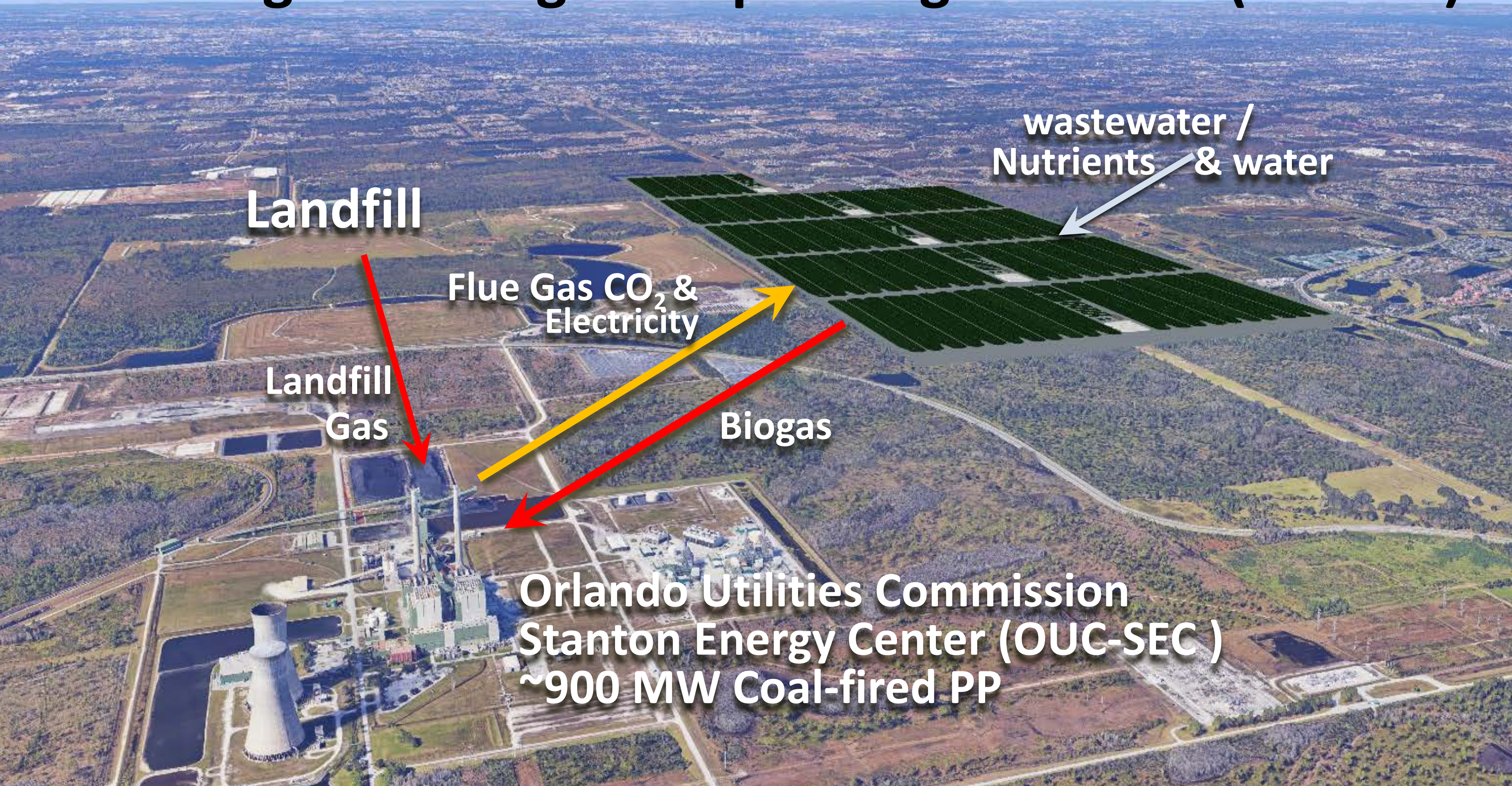

Orlando Utilities Commission Stanton Energy Center (OUC-SEC)
two ~450 MW Coal-fired PP


Orlando Utilities Commission
Stanton Energy Center (OUC-SEC)
~900 MW Coal-fired PP

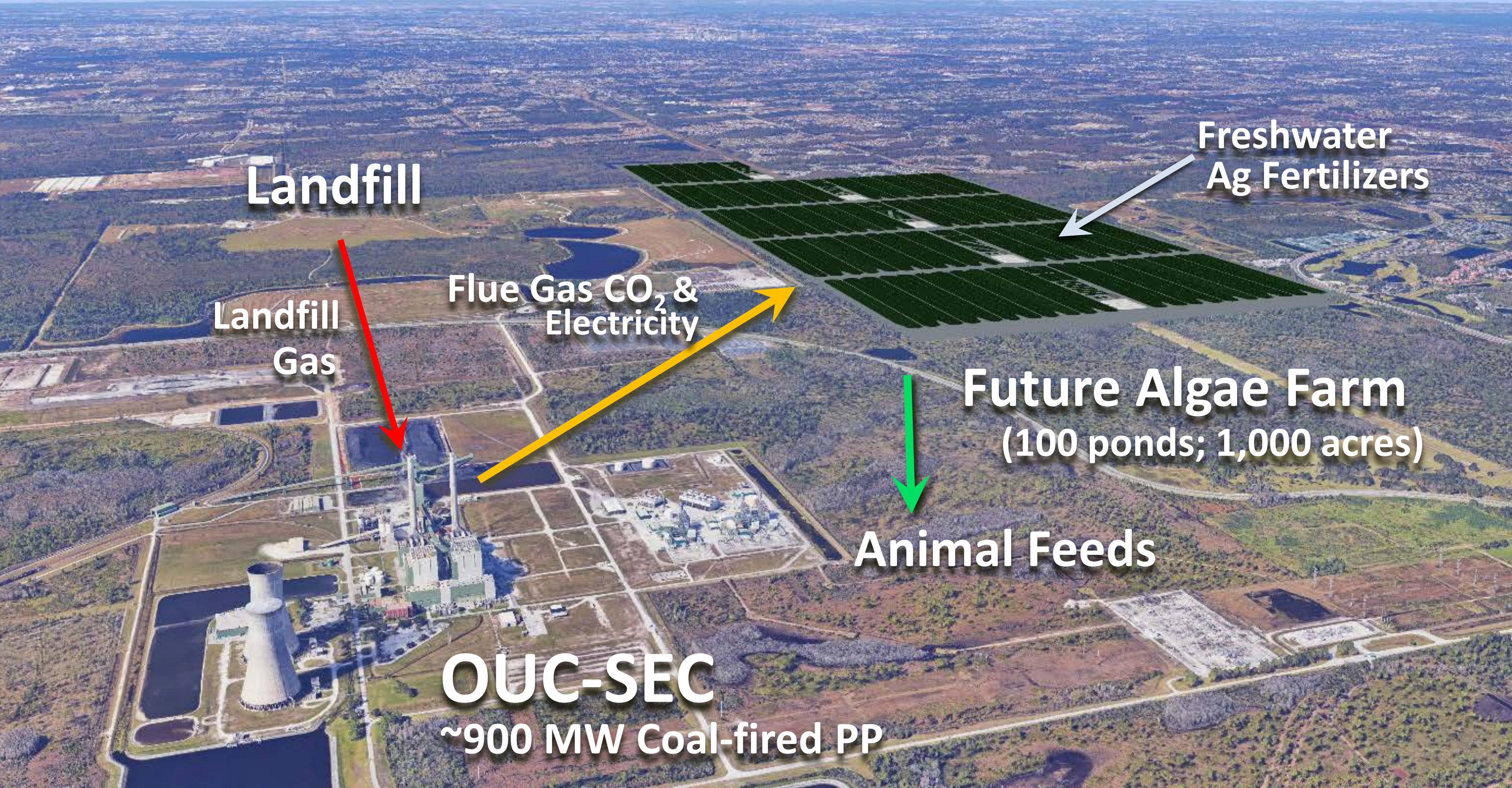



Future Algae Farm
(100 ponds; 1,000 acres)

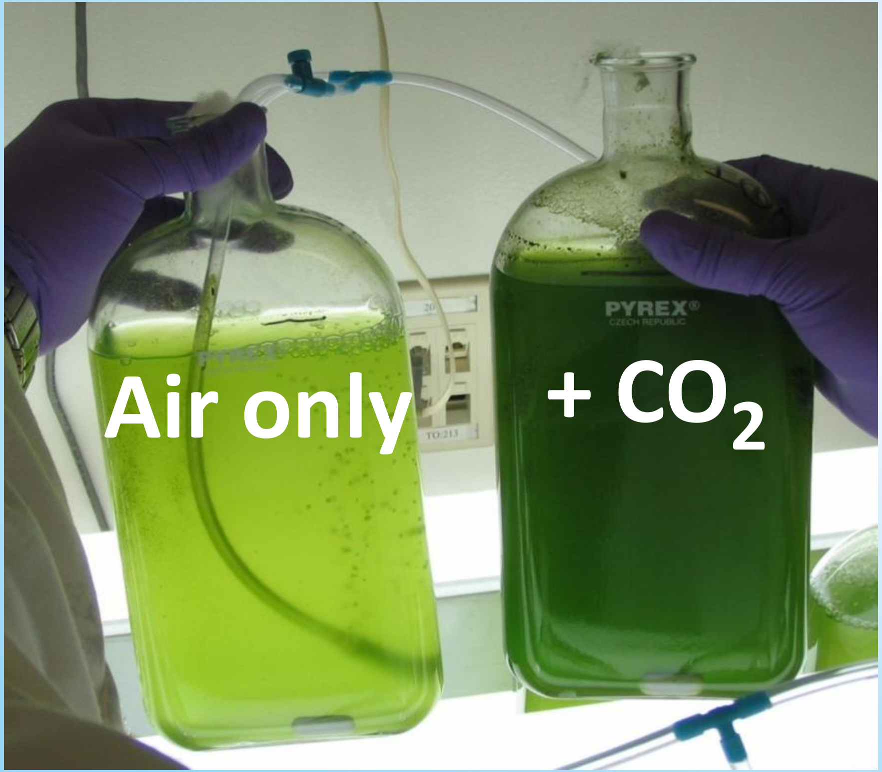
Case 1. Algae → biogas for power generation (1st Year)



Case 2. Algae → animal feed production (next year)



Technology Fundamentals/Background



Supplying CO_2 to algal cultures allows for high biomass productivity and complete nutrient assimilation during wastewater treatment or in recycling of algal residues after biofuels conversion / extraction

Technology Background: Current Commercial Microalgae Production Technology - Earthrise Nutritionals LLC, Calif.

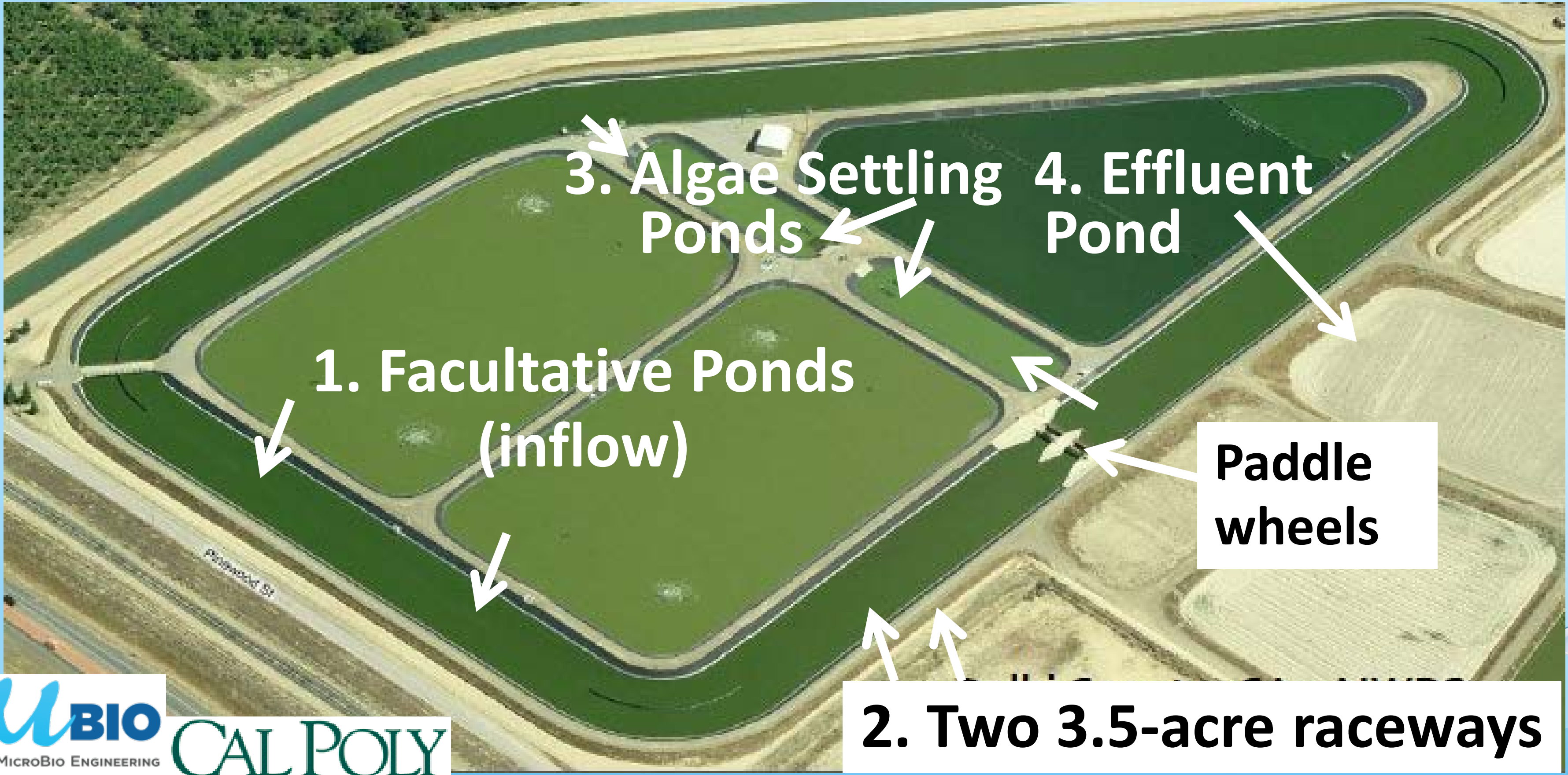
~50 acres of raceway, paddle wheel mixed ponds for Spirulina production


Paddle wheels →


Paddle wheels→
Cyanotech
Kona, Hawaii

Technology Background: Municipal Wastewater treatment

Delhi, CA, Site of DOE BETO ABY and STTR Projects by MBE / CalPoly



At Delhi algae are coagulated, settled ,solar dried.

~100,000 gallons of 3% solids algae in decanted settling basin

Concrete drying pad

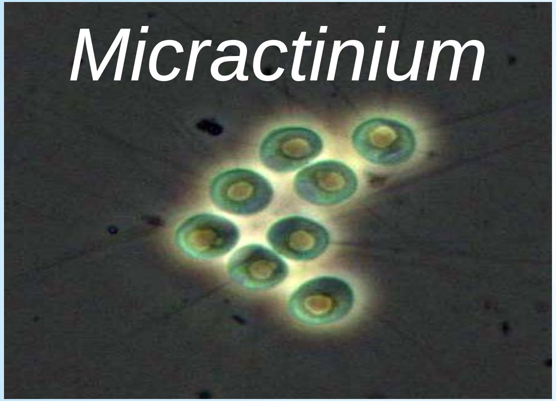
Algae Field Station - San Luis Obispo, Calif.

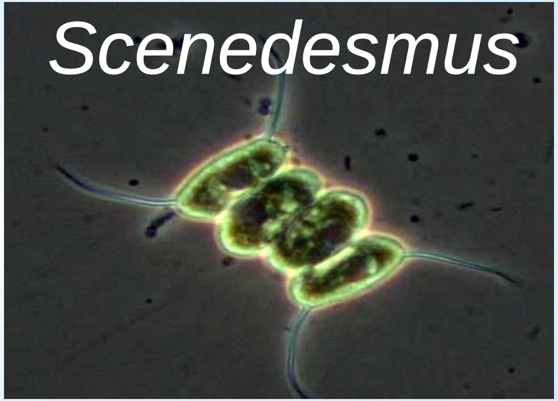
Research on algal wastewater treatment and Biofuels

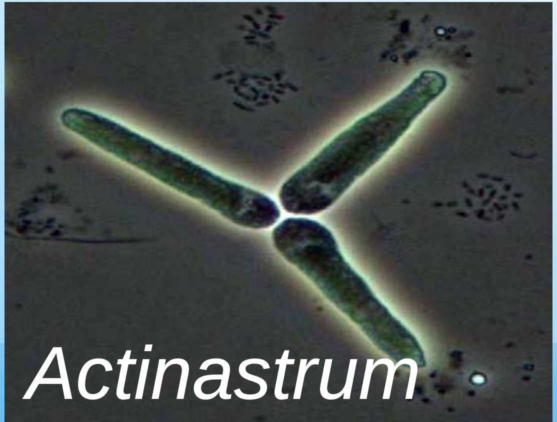
CAL POLY

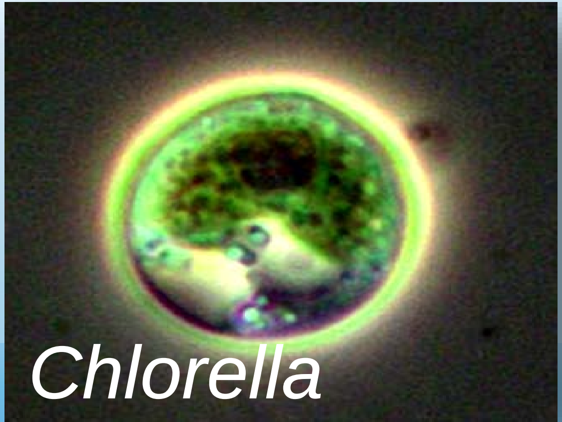
BIO
MicroBio Engineering

Green algae typical of fresh water algal mass cultures. Strain control and crop protection still major R&D needs.









Anaerobic Digestion Technology - Low Cost Design for Algae Digestion: 5-acre covered lagoon digester, California dairy

Technical & economic <u>advantages</u> of algal CO_2 capture

- **Higher productivity than other biofuel systems**
- **Can assimilate CO_2 from flue gas directly**
- **Can treat wastewater and reuse nutrients**
- **Can use non-agricultural water sources**

Prior TEA and LCA studies by the MicroBio Engineering Inc. team

Lundquist, T.J.; I.C. Woertz; N.W.T. Quinn; J.R. Benemann (2010). <u>A Realistic Technological and Economic Assessment of Algae Biofuels,</u> Report to Energy Biosciences Institute, U. Calif. Berkeley, California

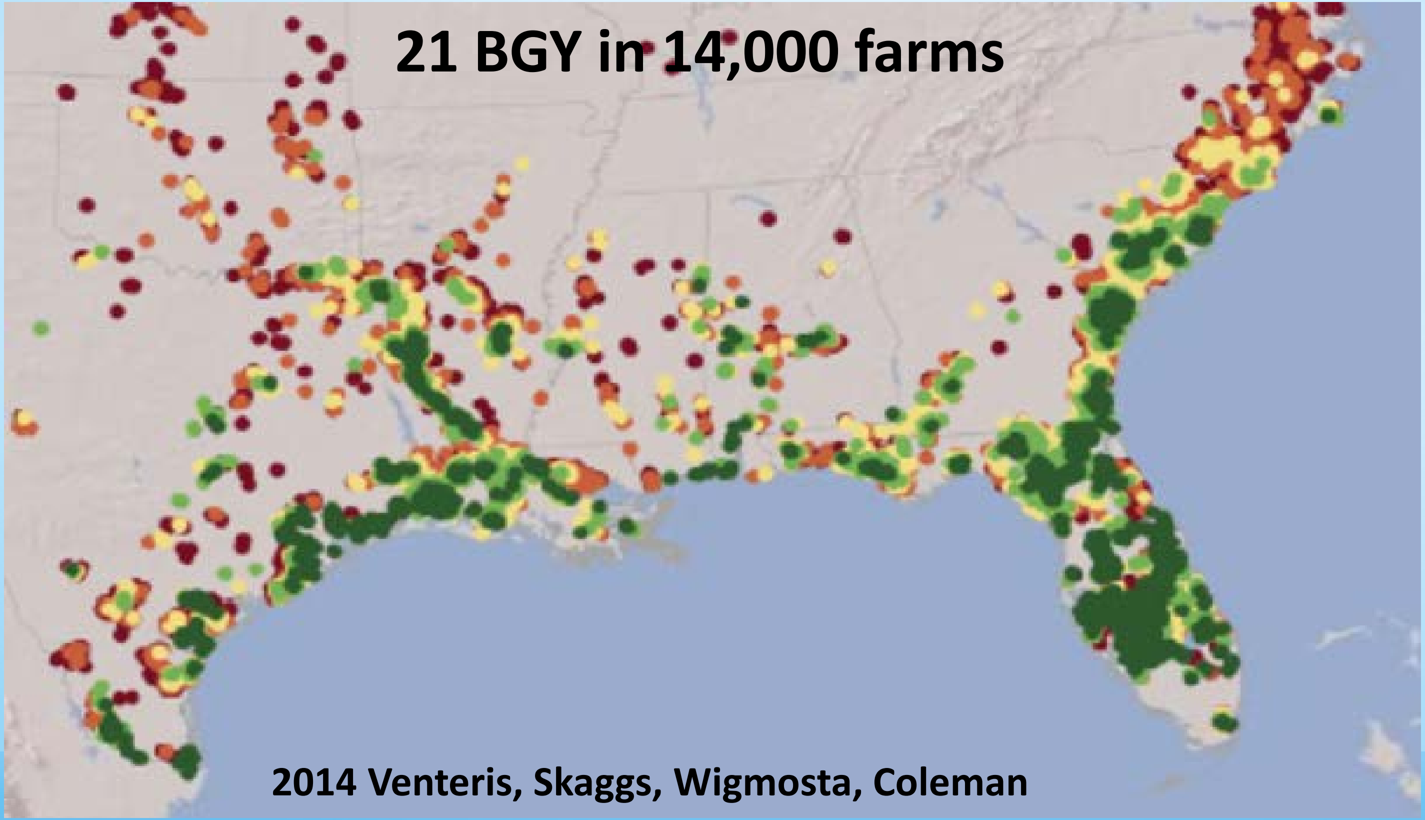
Woertz, I.W., J.R. Benemann, N. Du, S. Unnasch, D. Mendola, B G. Mitchell, T.J. Lundquis (2014) "Life Cycle GHG Emissions from Microalgal Biodiesel – a CA-GREET Model" *Env. Sci. Tech. 48*: 6060–68

Technical and Economic <u>challenges</u> to algal CO2 utilization from coal-fired power plants:

- Flue gas CO2 use limited by day/night and seasonal cycles.
- ~ 1/3rd of CO2 piped to ponds lost in transfer or outgassing
- Large land areas needed (~ 10 acre/Mwe) near power plant:
  - Land - near-flat, on/near grid, relatively low cost...
  - Water – fresh, brackish, seawater, wastewaters .
- Limited by climate to lower latitudes (see next slide)
- <u>Undeveloped technology - costs are currently are very high</u>

5 billion gallons per year (BGY) of algae biofuel could be produced using municipal wastewater use; 21 BGY with 'stand alone' systems.

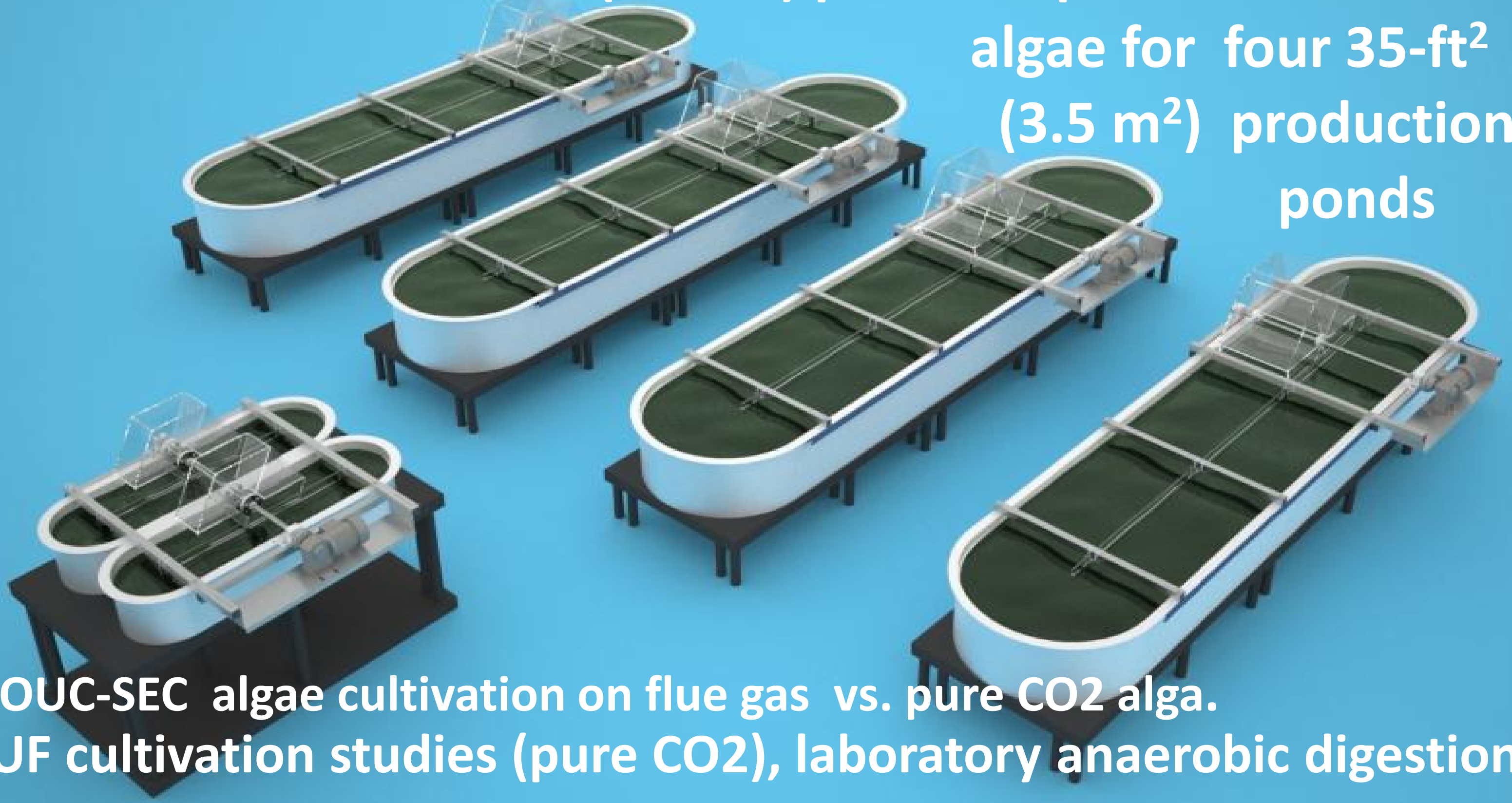
This DOE NETL Project examines both options at the OUC-SEC site in FL



1st Year Experimental Work at OUC-SEC and U.Florida

- Operate four 3.5-m^2 ponds at each location
- At OUC Compare flue gas to pure CO_2
  - Productivity, Metals concentration (water & biomass)
- At OUC and UF determine seasonal productivities at optimized hydraulic residence times (HRTs)
- At UF: Determine methane yields at one biomass concentration in batch methane potential tests

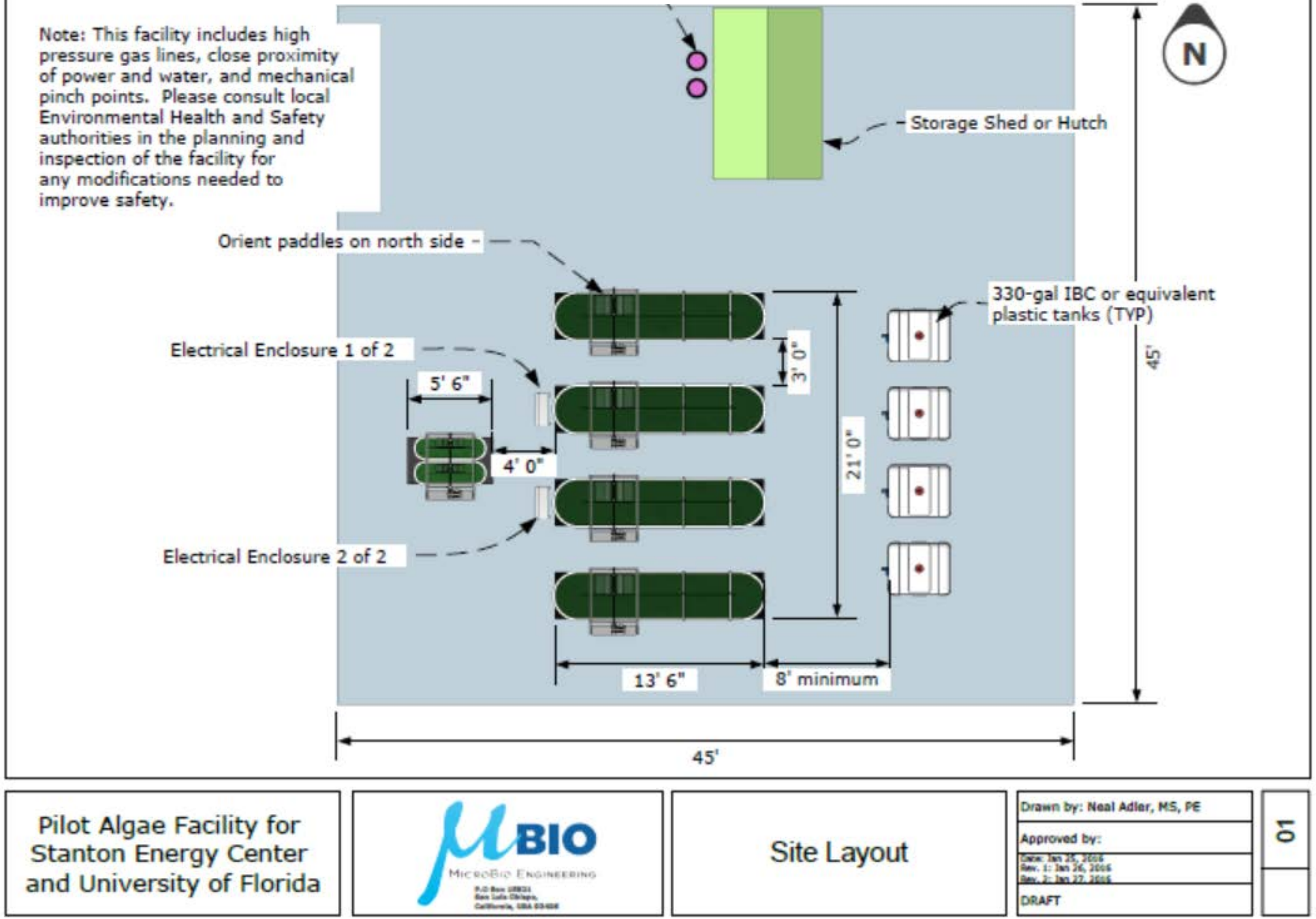
Experimental Algae Raceway™ Ponds fabricated by MBE and installed at both OUC-SEC and U. Florida



At each site two 5-ft^2 (0.5 m^2) ponds to produce inoculum algae for four 35-ft^2 (3.5 m^2) production ponds

– OUC-SEC algae cultivation on flue gas vs. pure CO2 alga.
– UF cultivation studies (pure CO2), laboratory anaerobic digestion studies .

General Site Layout at OUC and UF

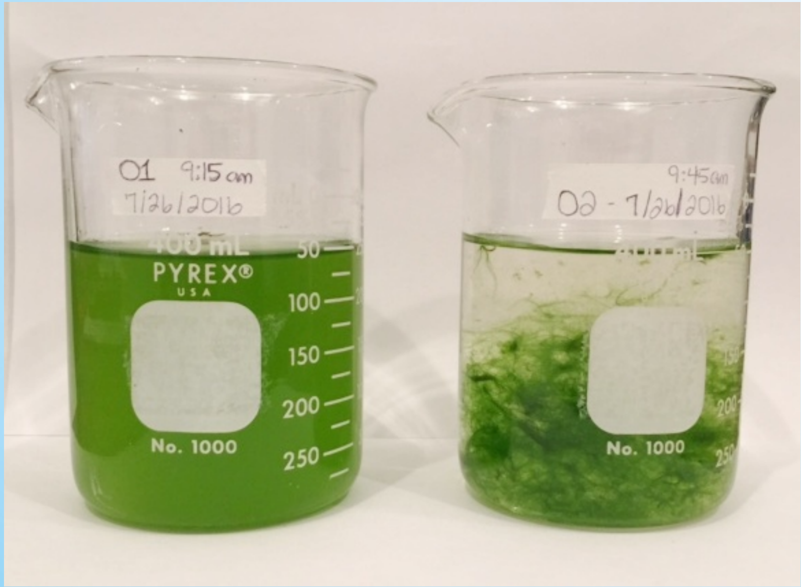


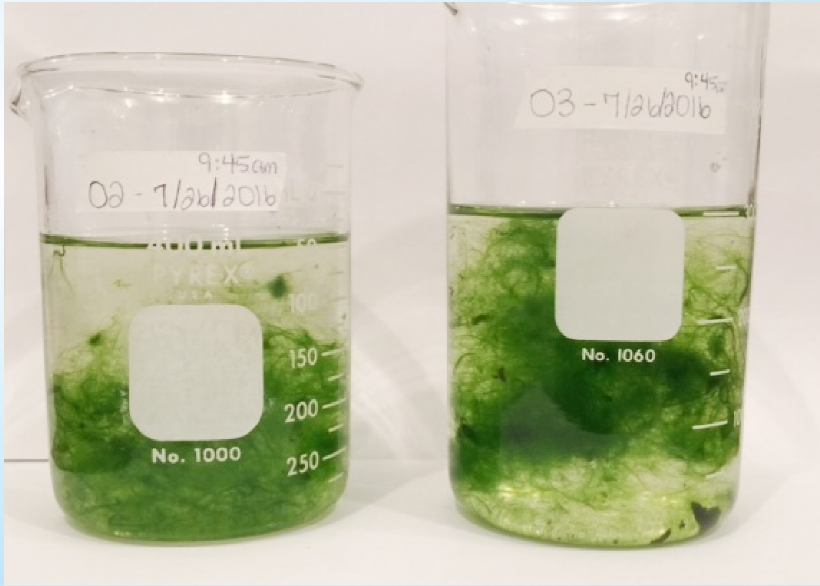
Flue gas from scrubbers to condensate traps to pump to pilot ponds

Flue gas → scrubbers → condensate traps → blower → pilot ponds

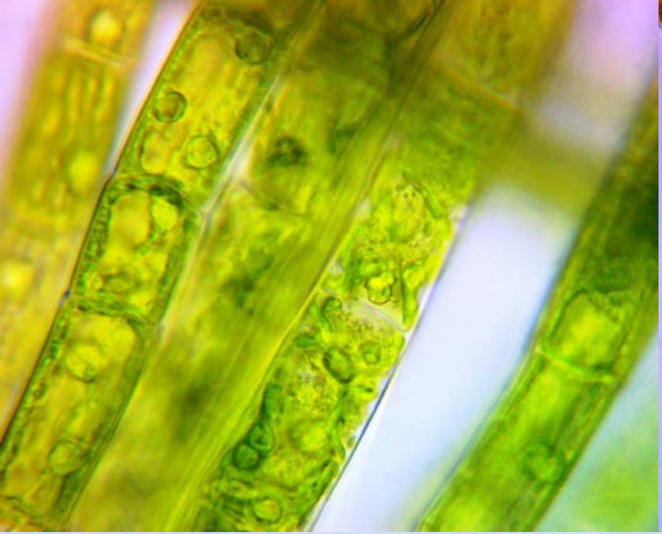

Fabiola
Costales
Ann
Wilkie
Cabbar
Dundar

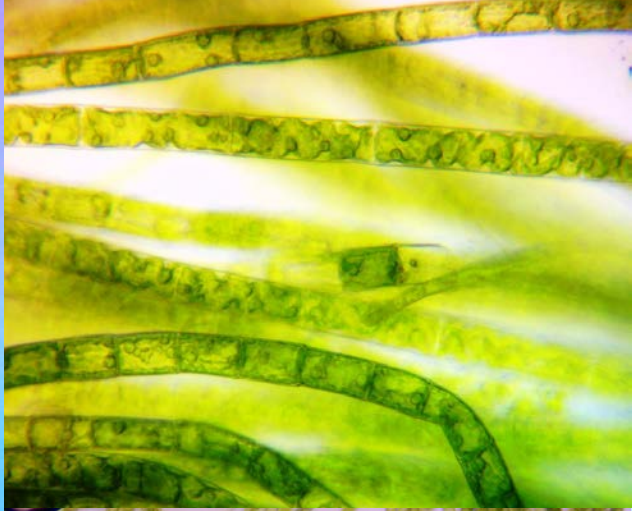
Filamentous algae dominate at OUC, but not consistently among ponds

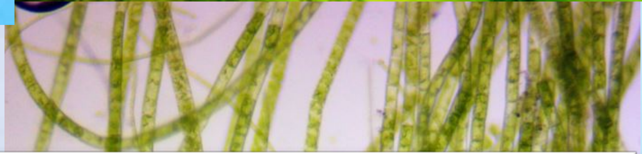




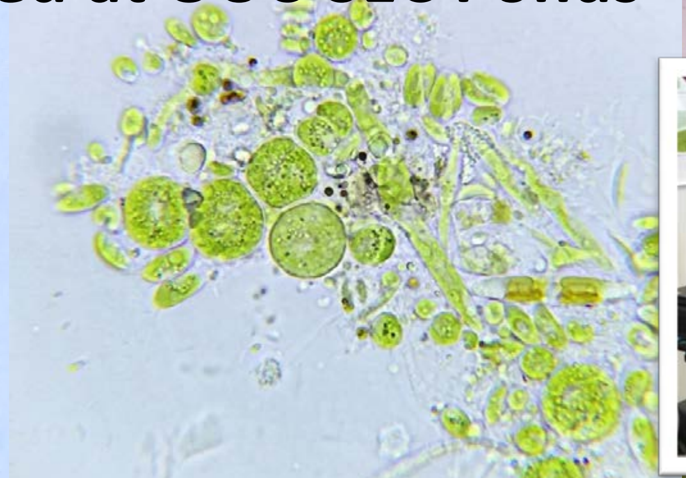
Hypothesis: Filamentous increase led to bias in measurement at OUC, not sampling all the biomass.





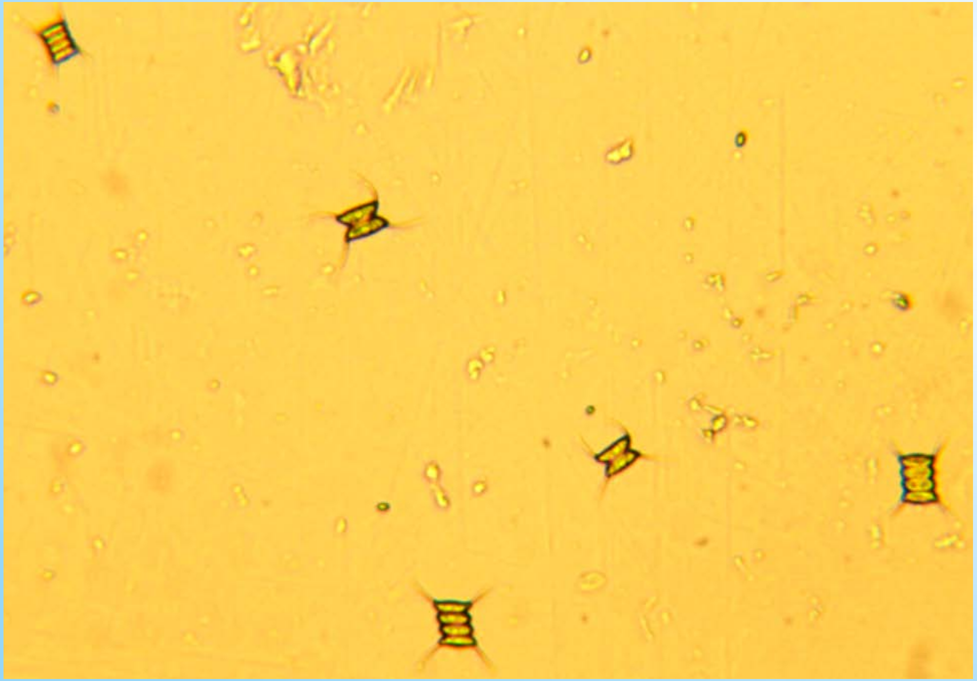


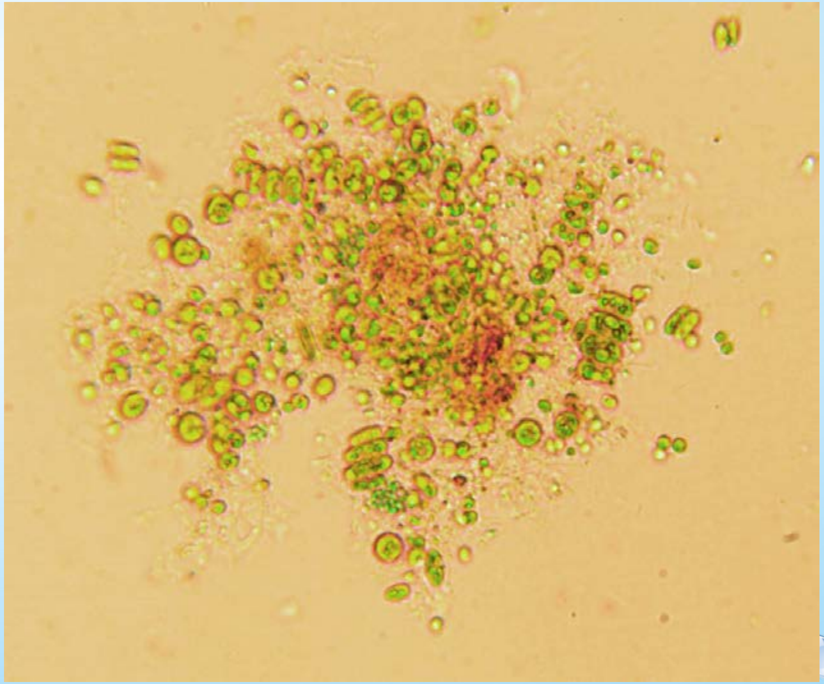
Microalgae observed at OUC-SEC Ponds



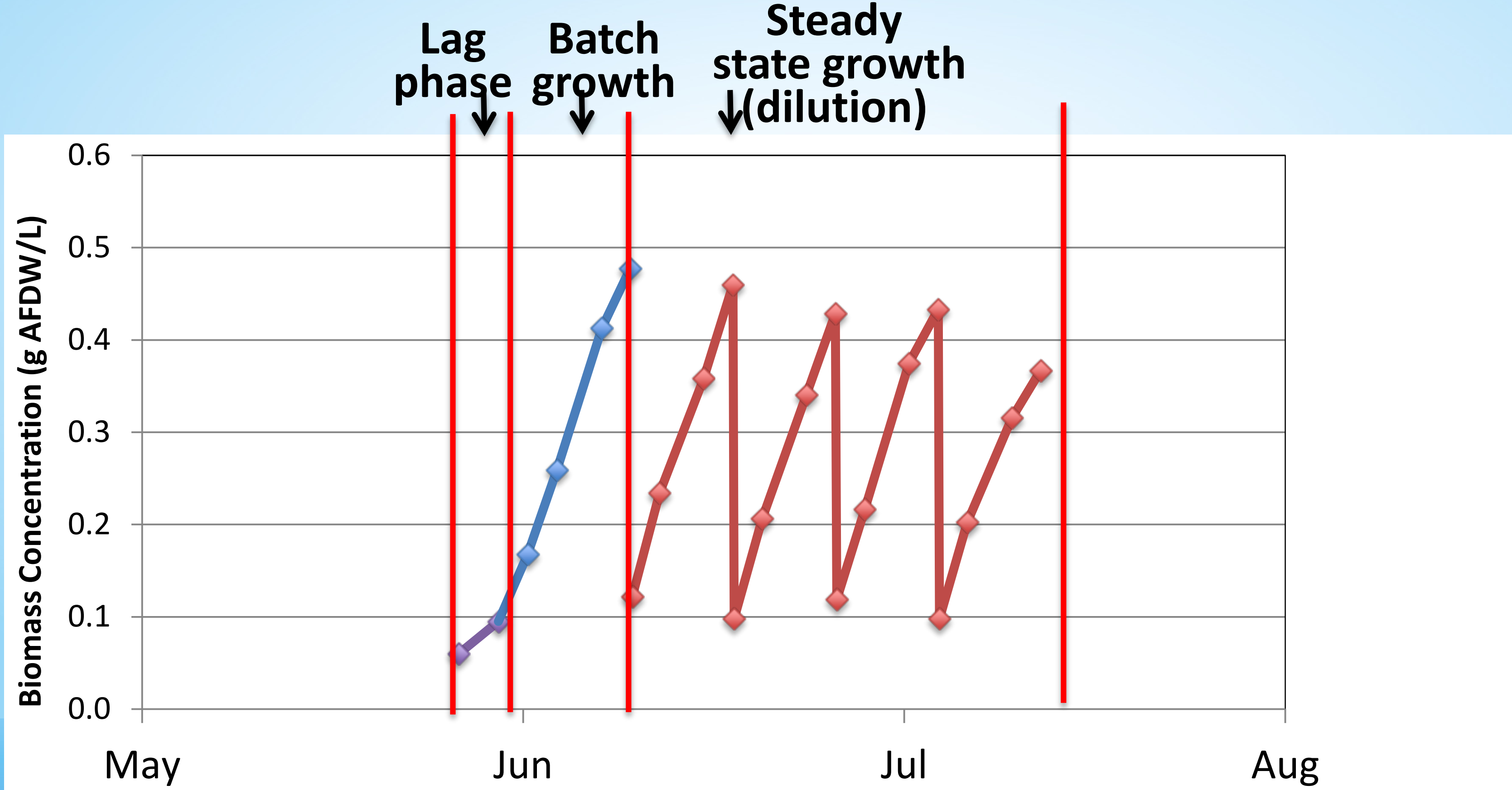
No filamentous at UF.
Some cultures bioflocculate (settle).

Micrographs of Algae from UF Ponds
More colloidal than OUC

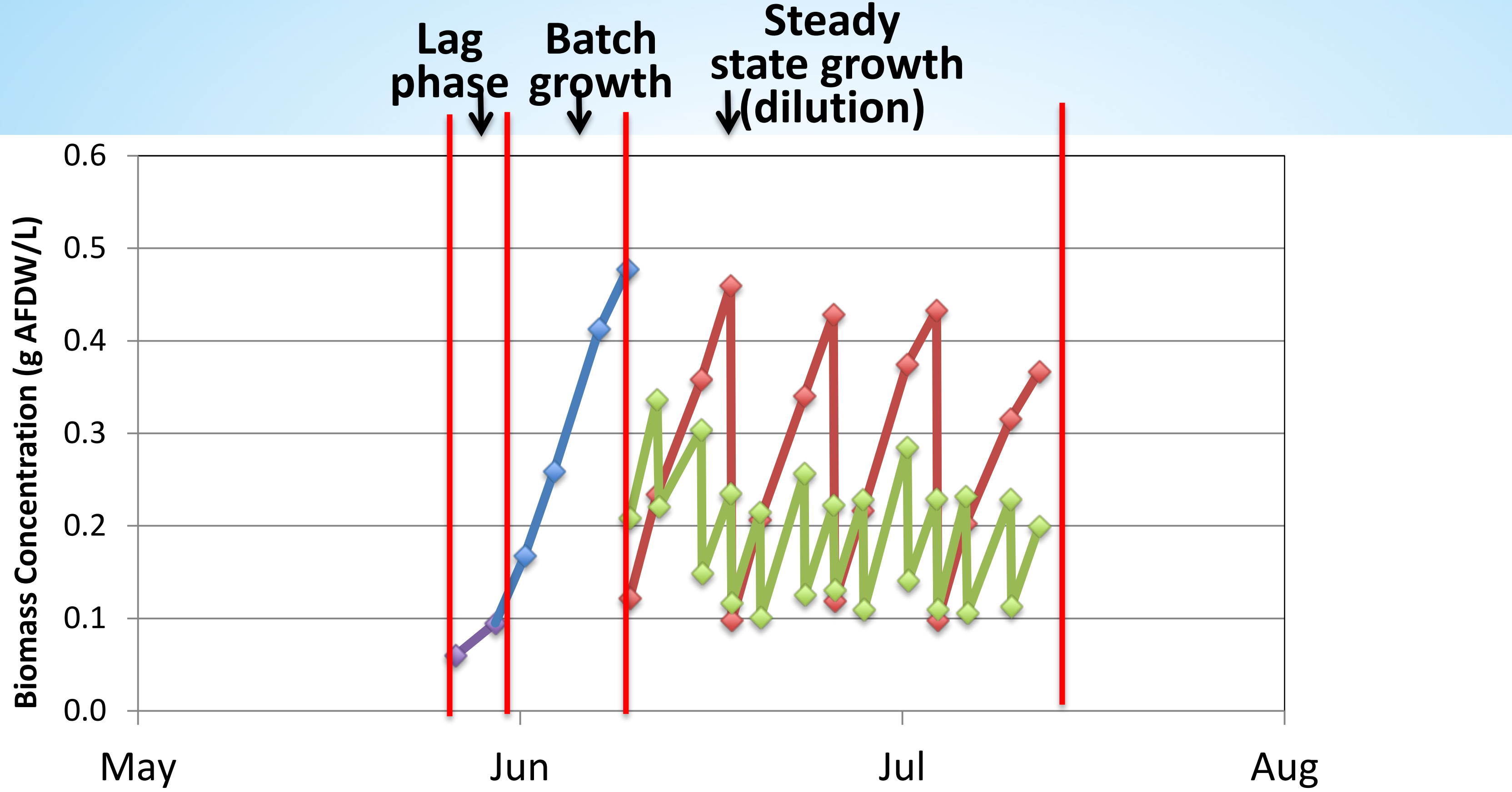




Example growth curve – “steady state” growth (weekly dilution) productivities similar to initial batch



Example growth curve – "steady state" growth: 3x/week dilutions in green, similar productivities as weekly dilutions



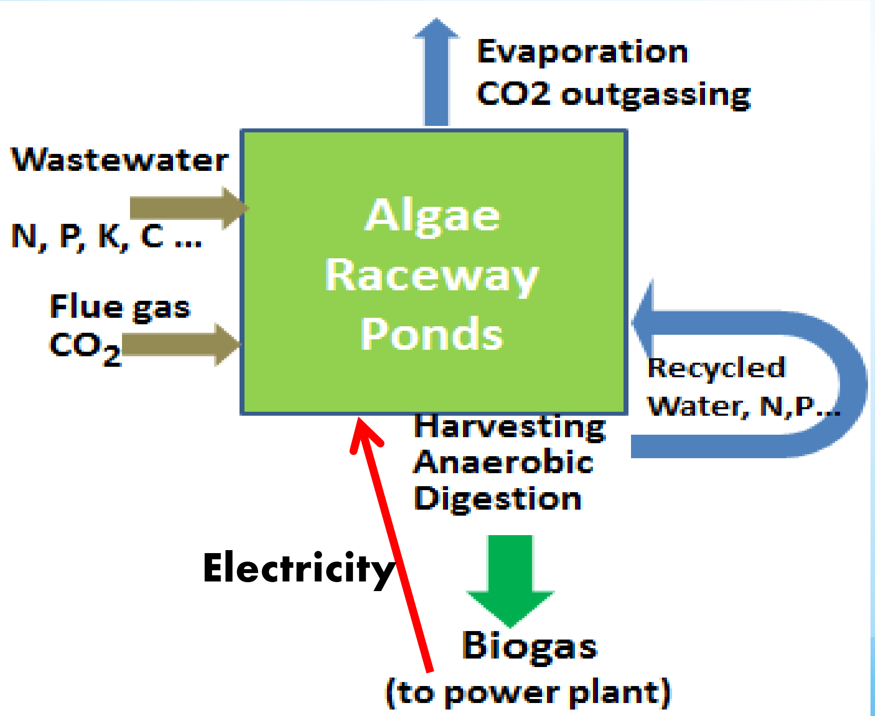
SEC and UF algae are being anaerobically digested at UF to determine CH_4 yield.

Techno-Economic Analysis

CO2 utilization Processes Investigated by this Project

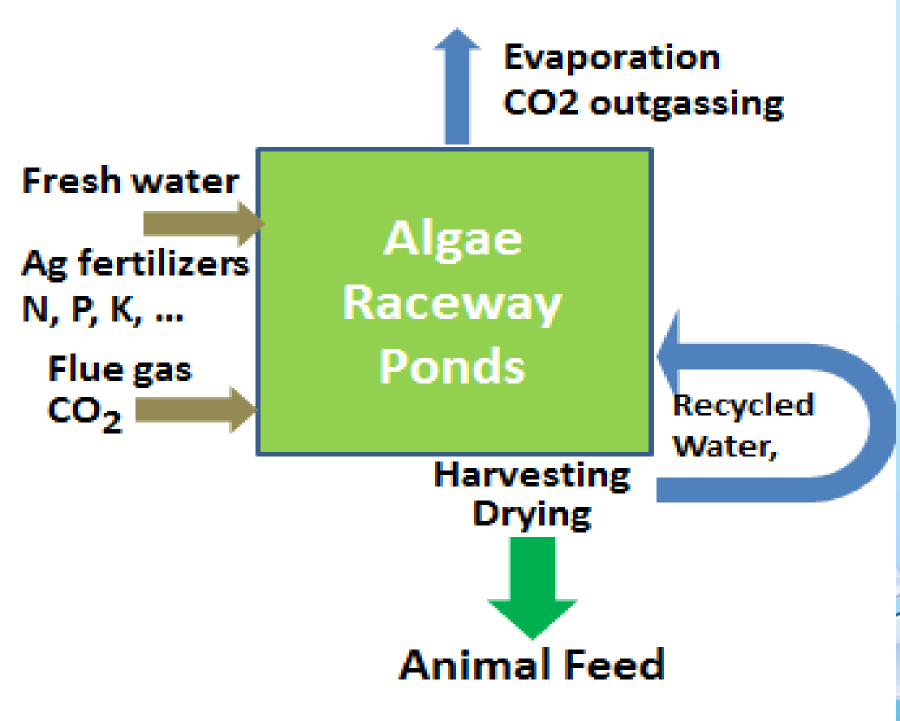
1. Biogas Production Case (1st Yr)

Nutrients recycled from anaerobic digesters, option of wastewaters inputs for water, nutrient make-up

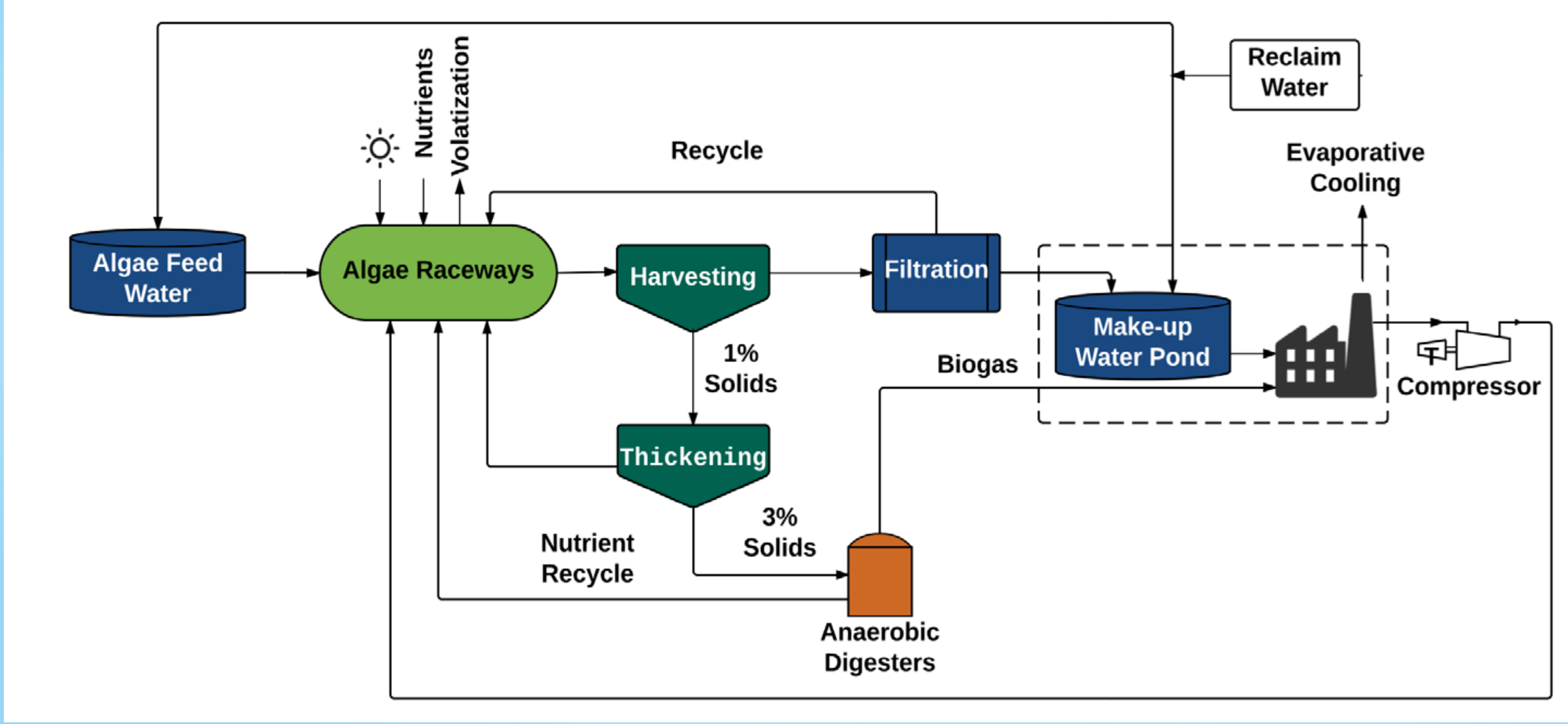


2. Animal Feed Case (2nd Yr)

Using fresh (and recycled) water & agricultural fertilizers as inputs



Case 1 (this year) : Biogas Process Flow Diagram



Site Selection near OUC-SEC

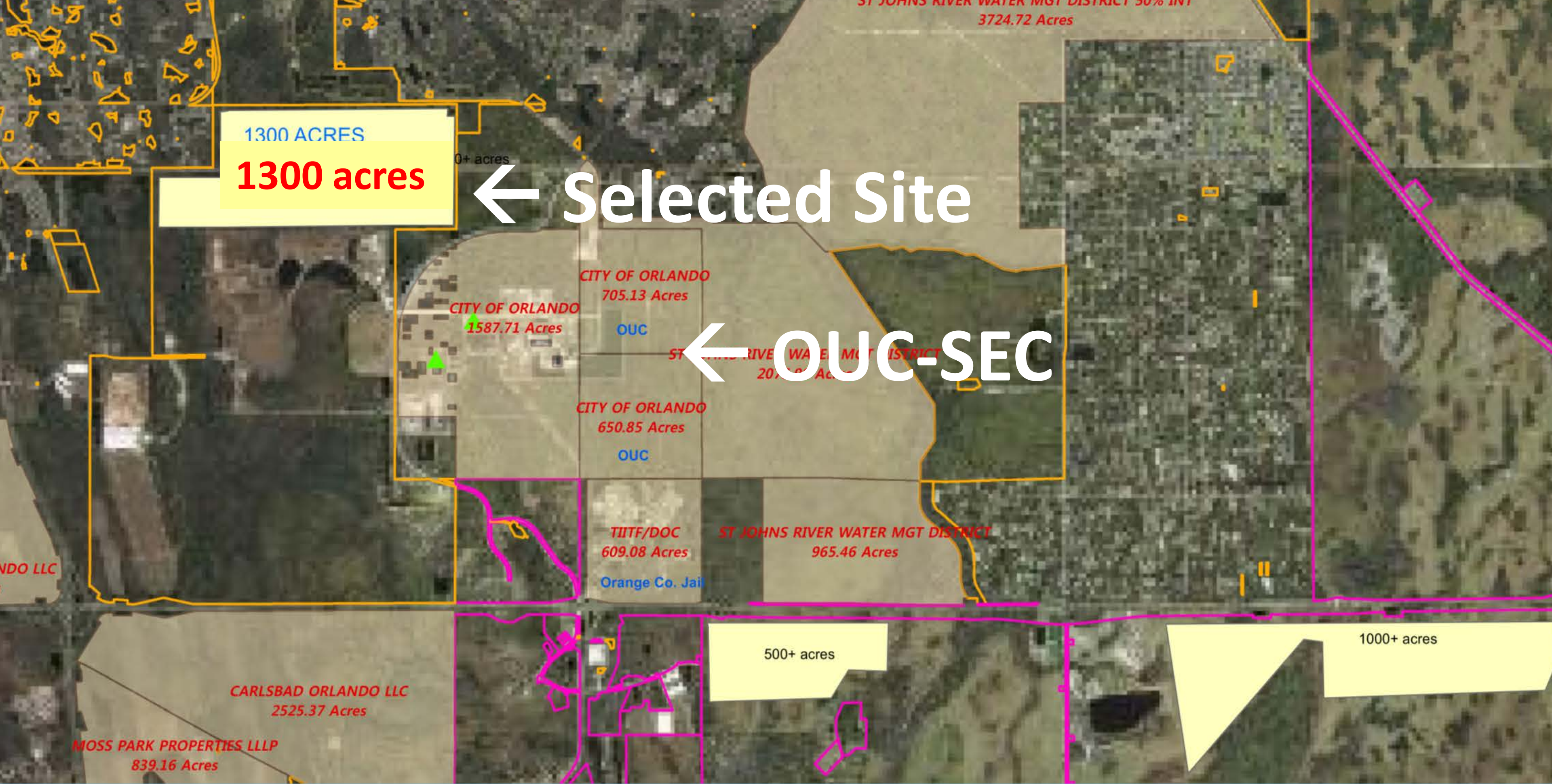
Site Requirements

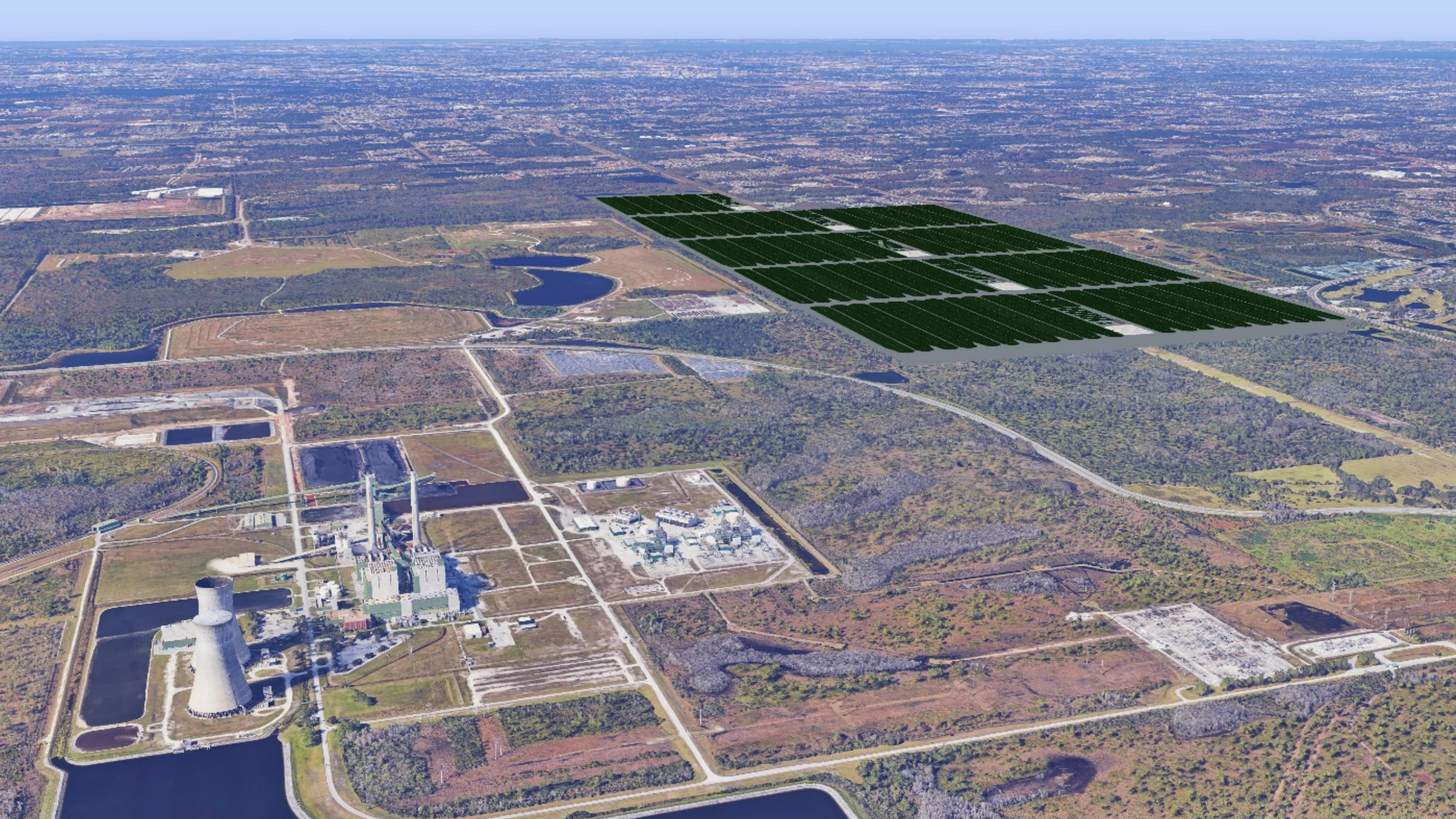
- 1,250 acre (500 ha) undeveloped site
  - For 1,000 acres (400 ha) of raceway pond water surface
- Within 10 miles from power plant

Major Local Environmental Parameters:

- Annual Average Precipitation: 135 cm (5.3 in)
- Annual Average Evaporation: 171 cm (6.7 in)
- **Net Annual Evaporation ~1 mm/day (0.04in)**

Potential Sites near OUC-SEC





Modeling - Power Plant Assumptions

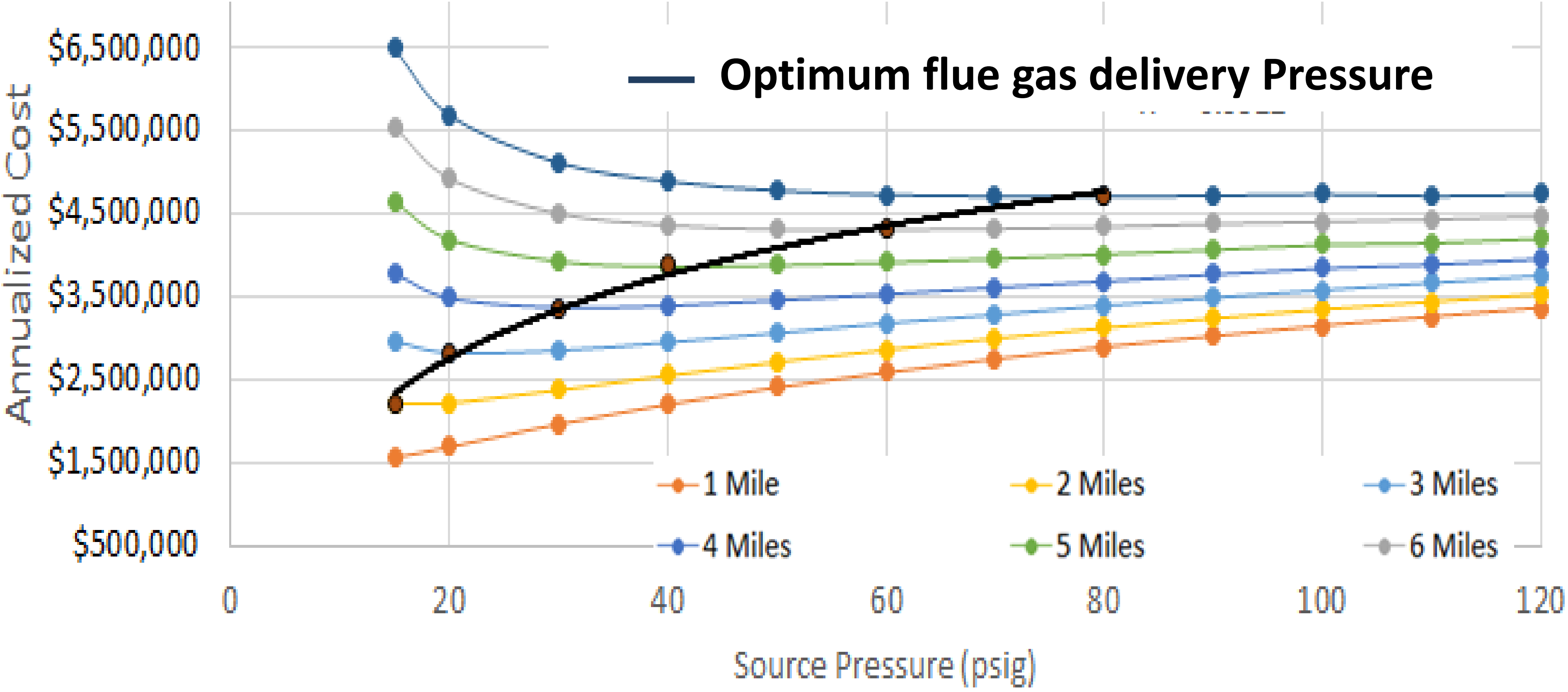
- Coal Type: Illinois Basin Bituminous
- 2014 CO_2 Emissions: 5,076,875 tons (Units 1 and 2)
- Flue gas composition (Post Desulfurization, Avg. of Unit1)
  - **11% CO_2**
  - **65 ppm SO_2**
  - **130 ppm NO_x**
  - **60 ppm CO**
  - **1.0 ug/scm Hg**

CONCLUSIONS: Contaminants have no significant effect on algal production or economics.

Flue Gas Conditioning and Transfer Operating Parameters

Parameter	Value
Operating Temperature	70 F
Operating Pressure	40 psig
Average Flow (15 g/m^2-d)	17,000 cfm @ 68 F and 1 atm
Peak Flow (4.5 g/m^2-hr)	122,000 cfm @ 68 F and 1 atm

Effect of Operating Pressure on Flue Gas Transport Costs*



*with $75/t imputed CO2 emissions cost from the power used by compressors

Modeling - Major Assumptions*

- Annual Average Daily Productivity 33 g/m^2-day, of which:
  - 15 g/m^2-day algae growth from CO_2 supplied from flue gas
  - 18 g/m^2-day algae from C recycled from anaerobic digesters
- 4.5 g/m^2-hr: Peak summer productivity on flue gas CO_2
- 45% Overall loss factor in flue gas CO2 supply to ponds
- 90% efficiency in gravity harvesting (losses recycled to ponds)
- Biogas Production: 0.32 L Methane/g VSS
- Entire digester effluent recycled to ponds. N,P,K losses~10%/y

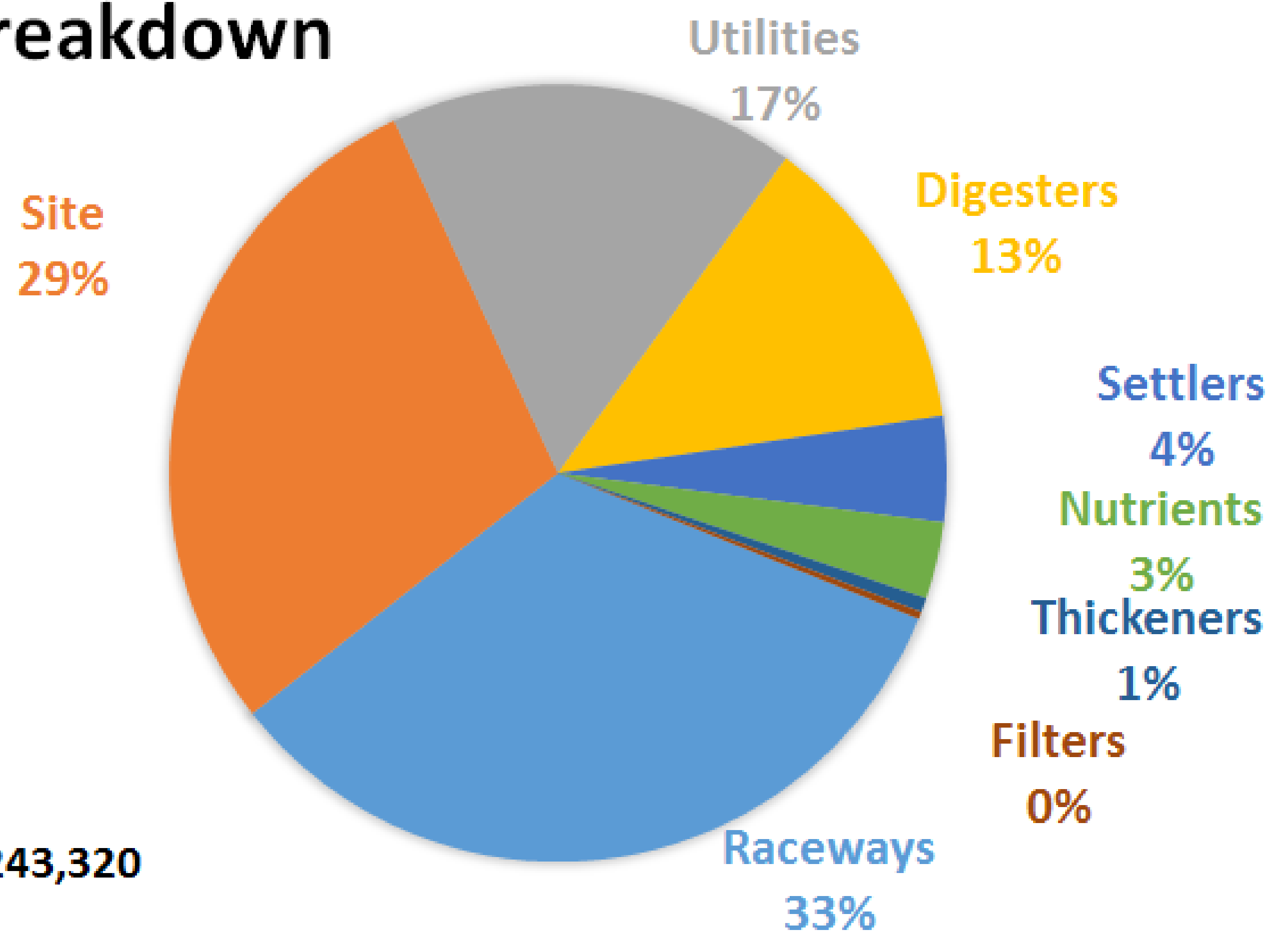
*MicroBio Engineering Inc. Experimental data, analysis and projections.

CAPEX:

~100 million for 1000 acres of ponds area

Site (of which Land $12,334,208)	$23,805,271
Utilities (Electrical Distribution ($7,587,378)	$14,027,164
Flue Gas/Nutrients	$2,651,222
Raceways (of which liner $16 million)	$27,617,615
Settlers	$3,632,126
Thickeners	$493,982
Digesters	$10,514,985
Filters	$250,000
Subtotal	**$82,992,366**
A/E Fee (5%)	$2,544,007
GC Fee (5%)	$2,544,007
Working Capital (5%)	$2,544,007
Contingency (10%)	$8,299,237
Start-up and Permitting (4%)	$3,319,695
Total Capital Expense	**$102,243,320**

CAPEX Breakdown



Total: $102,243,320

Project Financing

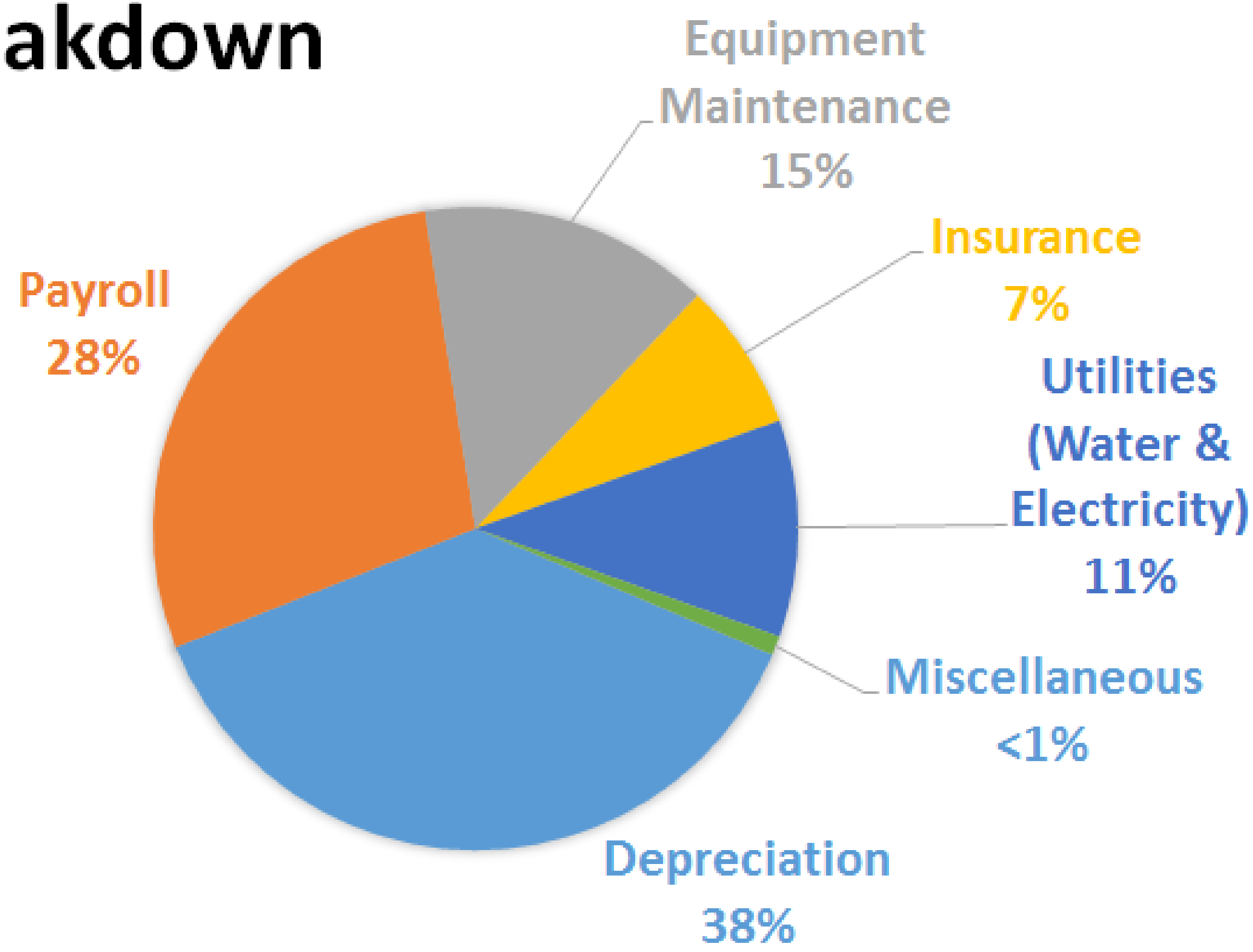
Capital Required	$102,243,320
Percentage of Capital financed by debt	100%
Percentage of Capital financed by equity	0%
Total Borrowed	$102,243,320
Bond Length (yr)	20
Interest Rate	8%
Bond Repayment	**$10,413,708**

OPEX

~10 million/yr for 1,000 acres of ponds area (+ ~$10 million in bond payments)

Description	Total
Operators and Engineers	$1,700,000
Manager and Director	$750,000
Assistants	$300,000
Lab and Office Supplies	$50,000
Employee Training	$42,000
Insurance	$720,000
Depreciation	$3,632,808
Make-up Water	$210,310
Nutrients (incl. CO_2 Distribution)	$384,609
Raceways	$176,199
Settlers	$207,795
Thickeners	$13,254
Anaerobic Digesters	$39,071
Filters	$18,165
Equipment Maintenance	$1,413,163
Total	**$9,657,374**

OPEX Breakdown



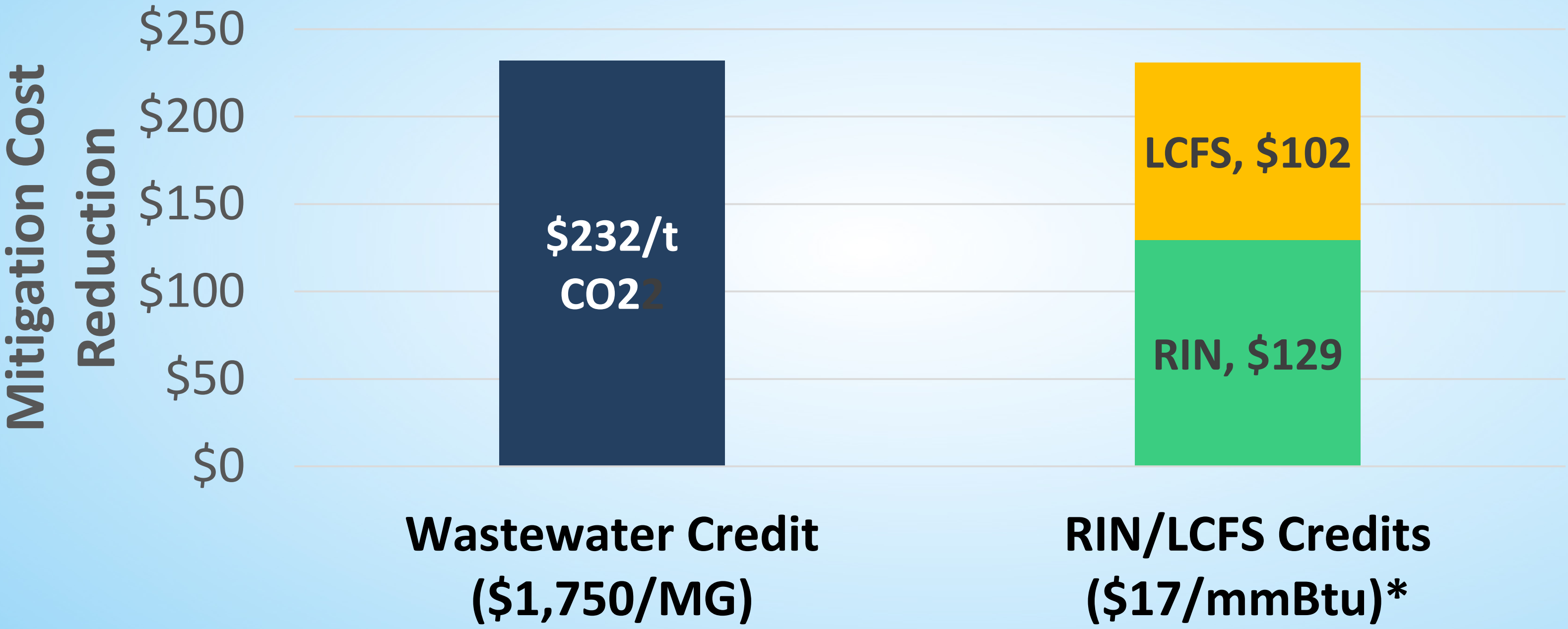
Total: $9,657,374

Initial TEA Summary

Bond Repayment	**$10,413,708**	**/yr**
Operating Expense	**$9,657,374**	**/yr**
Total Annualized Cost	**$20,071,082**	**/yr**
Income gross biogas @$2.00/MMBtu*	**$1,043,384**	
Cost to Mitigate CO2 at OUC-SEC	**$497**	**/mt CO2 mitigated**

* All biogas sold to OUC-SEC @ $2/MMBTU for combustion to replace coal.
All power used in process purchased from OUC-SEC at $0.038 /kWhr

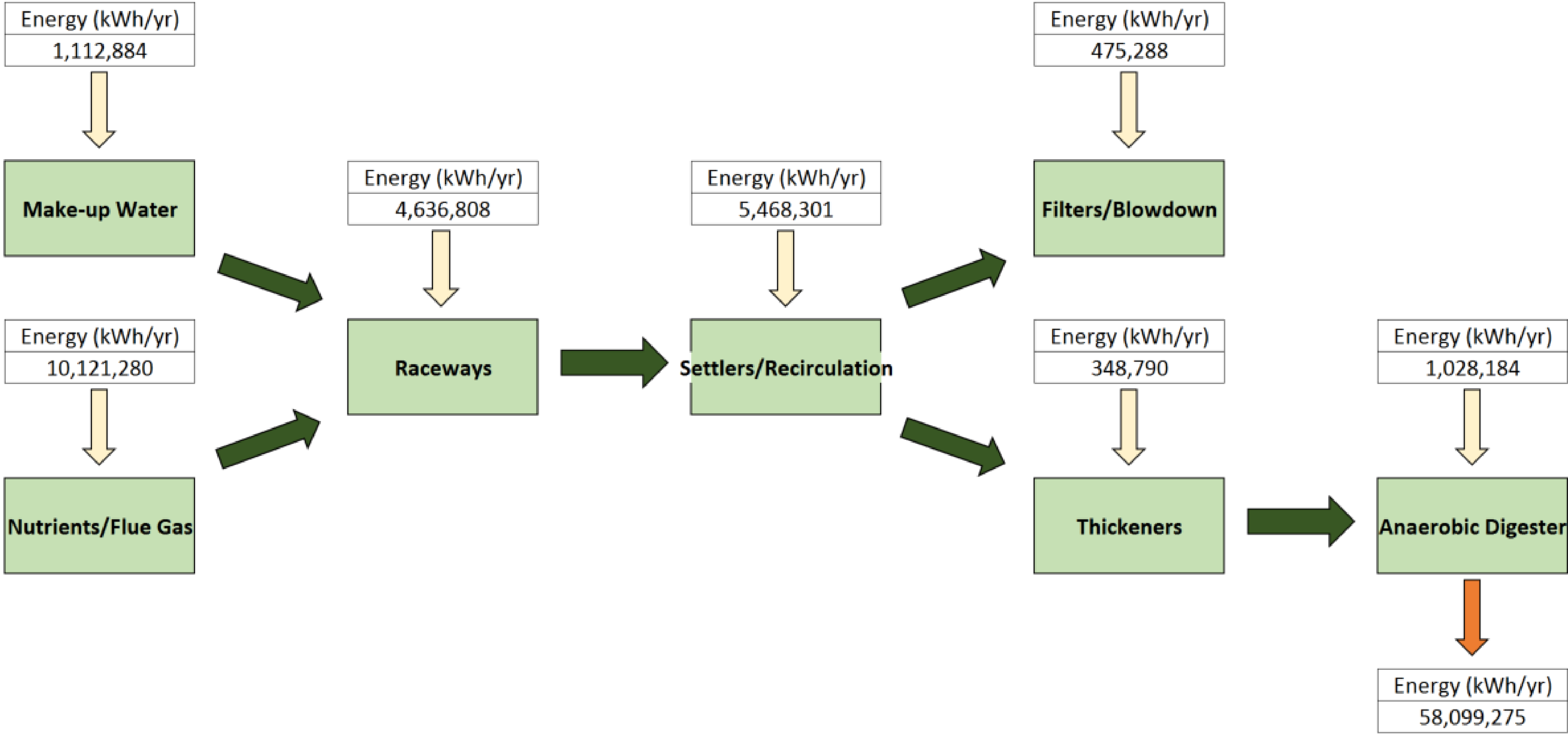
Potential Revenue Sources



*Based on treating 12 MGD, ~120,00 people equivalent wastes

Life Cycle Assessment

Energy Balance



Energy Balance

Utilities	Energy		GHG Equiv.	
Make-up Water Pumping	1,112,884	kWh/yr	1,106,485	kgCO2eq/yr
Nutrients				
Flue Gas Transport	5,953,492	kWh/yr	5,919,259	kgCO2eq/yr
Nitrogen Fertilizer (Urea/DAP)	4,167,788	kWh/yr	1,380,081	kgCO2eq/yr
Raceway Mixing	4,636,808	kWh/yr	4,610,146	kgCO2eq/yr
Settlers				
Supernatant Pumping (Recirculation)	4,775,491	kWh/yr	4,748,032	kgCO2eq/yr
Harvesting	262,800	kWh/yr	261,289	kgCO2eq/yr
Subnatant Pumping	430,010	kWh/yr	427,538	kgCO2eq/yr
Thickeners				
Supernatant Pumping (Recirculation)	146,920	kWh/yr	146,075	kgCO2eq/yr
Harvesting	65,700	kWh/yr	65,322	kgCO2eq/yr
Subnatant Pumping	136,170	kWh/yr	135,387	kgCO2eq/yr
Anaerobic Digesters				
Biogas Transport	958,709	kWh/yr	953,197	kgCO2eq/yr
Nutrient Recycle Pumping	69,474	kWh/yr	69,075	kgCO2eq/yr
Filters	478,036	kWh/yr	475,288	kgCO2eq/yr

Initial LCA Results Summary

Annual Fuel Production (Biogas)	715,462,048	SCF
Gross Annual Biogas Energy Content	521,692	MMBtu
Net Annual Electrical Generation (38% Eff)	39,075,528	kWh
Net Energy Ratio (internal to process)*	0.40	
Net Annual GHG Emissions Reductions	(38,303)	metric tons CO_2
CO_2 Emissions Reductions from both Units	**0.8**	**%**

*** = (Parasitic Energy)/(Biogas Electricity Generated by OUC-SEC coal-fired power plant)**

Major Risk Factors – and Risk Reduction Strategies

- **Algae Cultures –** instability, productivity, media recycle, harvest efficiency. **Strategy:** long term R&D at scale is required; need better strain selection.
- **Site Selection -** Ownership, uses, zoning, rights of way, regulations, soils and geotechnical, flood plain, distance. **Strategy:** keep looking , 100 ha, sites
- **Anaerobic Digestion -** Design and operations of long-residence in-ground digesters; CH_4 yield 0.32 L/g volatile solids. **Strategy:** R&D lab and at scale.
- **CAPEX** - All aspects of design have uncertainties, risks. Liner a major one. **OPEX -** Labor, power costs, water supply, bond payments/ROI, indirect costs. **Strategy:** advance to pilot-scale for more realistic CAPEX-OPEX projections.
- **REVENUES -** Natural gas price. RINs. CO2 and wastewater treatment credits. **Strategy:** waste inputs from ~ 100,000 to >1 million population equivalent (pe) to provide nutrients and make-up water (evaporation, blow-down). Use biogas for vehicular fuels (RINs). Combine different credits, products.

Conclusions and Future Developments/Testing

Conclusions: CO2 emissions reduction from coal-fired power plants with microalgal processes will require:

-- Wastewater treatment, other revenues, CO2 credits

-- Process improvements for lower CAPEX and OPEX

Plans for Next Year: TEA/LCA animal feed production

Future Plans: scale-up algae biomass cultures at OUC-SEC

Commercialization: None planned in near term.

– **Need long-term process development and demonstration**


THANK YOU