Microalgae Commodities from Coal Plant Flue Gas CO2

DE-FE0026490, 10/01/15– 09/30/17, Andy Aurelio, Program Manager

Funding: DOE NETL: $863,327Orlando Utilities Commission (OUC) Cost Share: $282,640

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

MicroBio Engineering Inc.

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)**: **Stanton Energy Center (SEC)** power plant /site data; 0perate algae 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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- Facilities Designs
- Algae Equipment
- R&D, Enginnering Consulting
- Techno-Economic Analyses
- Life Cycle Assessments

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- Wastewater Reclamation
- Biofuels, Biofertilizers
- AquaFeeds, Nutritionals

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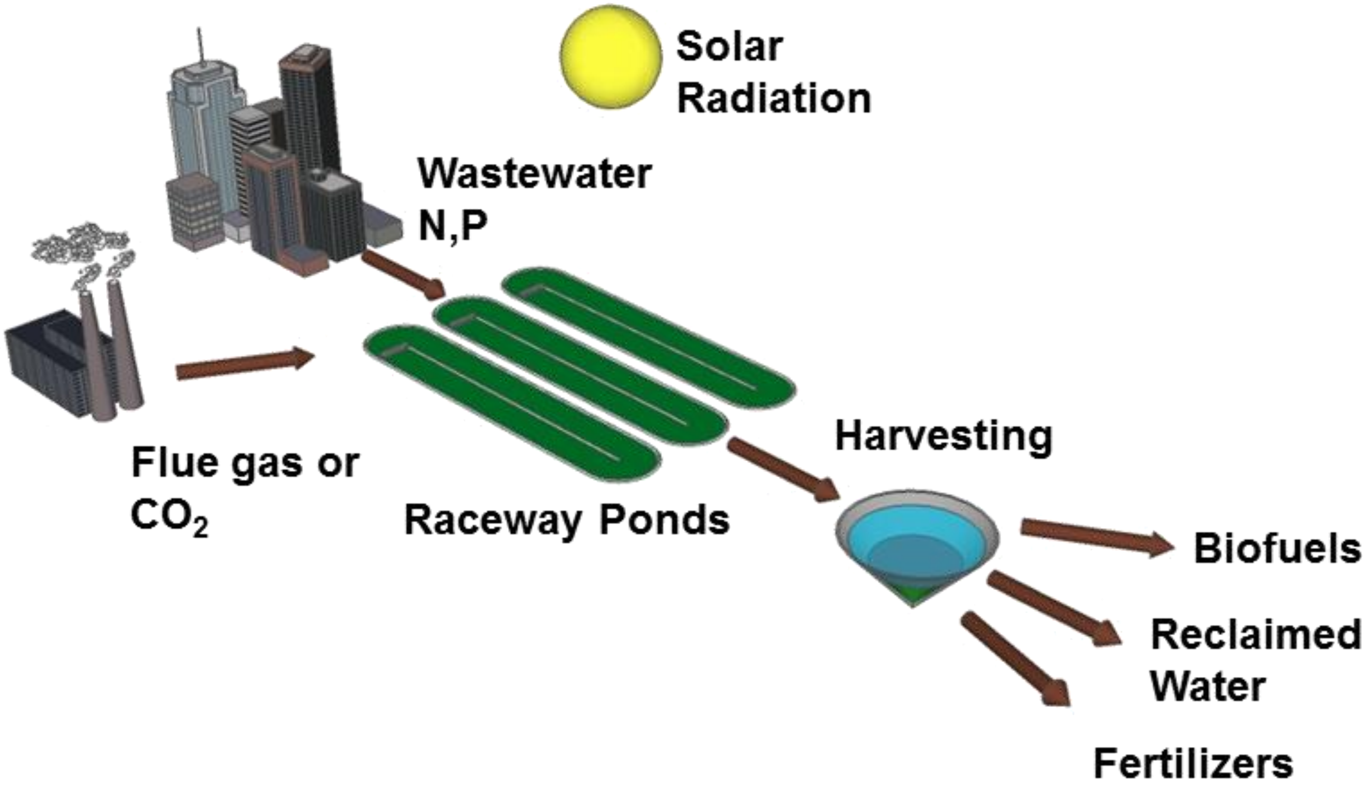
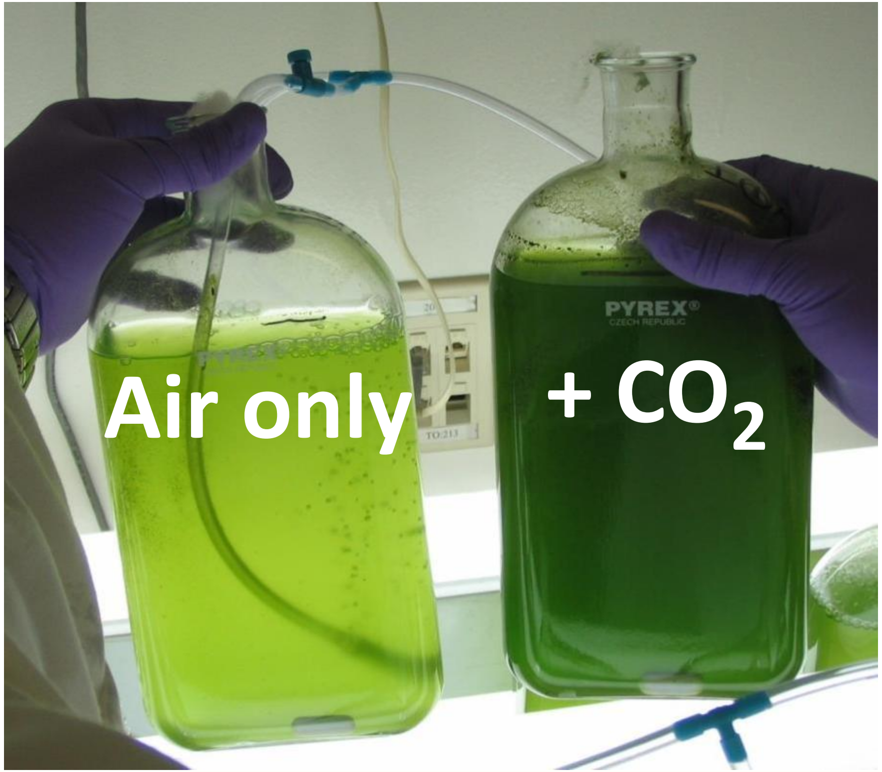
MicroBio Engineering Inc. RNEW® Process: Algal Wastewater Treatment with Biofuels Production, Water/Nutrients Reclamation, Biofertilizers

Recycle
Nutrients
Energy
Water



Algae cultures, wastewater treatment require CO_2



CO_2 supply maximizes algal biomass production and achieves complete nutrient assimilation in wastewater treatment.

Microalgae Municipal Wastewater treatment, Delhi, CA

Site of DOE BETO Funded Projects - MicroBio Engineering / CalPoly

μBIO MicroBio Engineering CAL POLY

Algae harvested by in-pond settling, then solar dried

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

Solar Dried Algae (for biofertilizer)

Concrete drying pad

Low-Cost Conversion of Algal Biomass to Biogas (CH_4/CO_2) based on covered lagoon anaerobic digester technology

(here 5 acre dairy wastewater digester in California)

DOE-NETL DE-FE0026490: Overall Project Objectives "Microalgae Commodities from Coal Plant Flue Gas CO2"

- 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.

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

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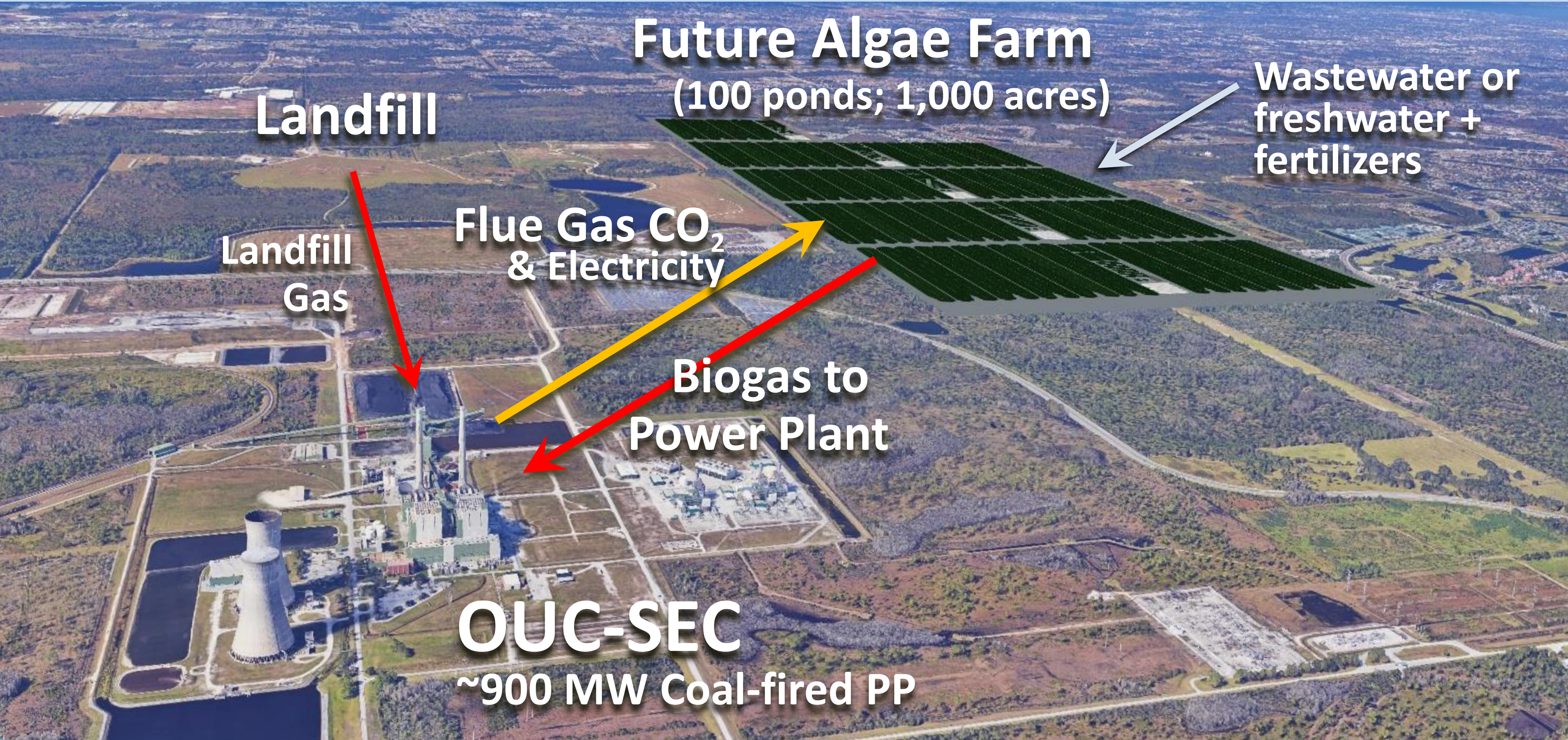
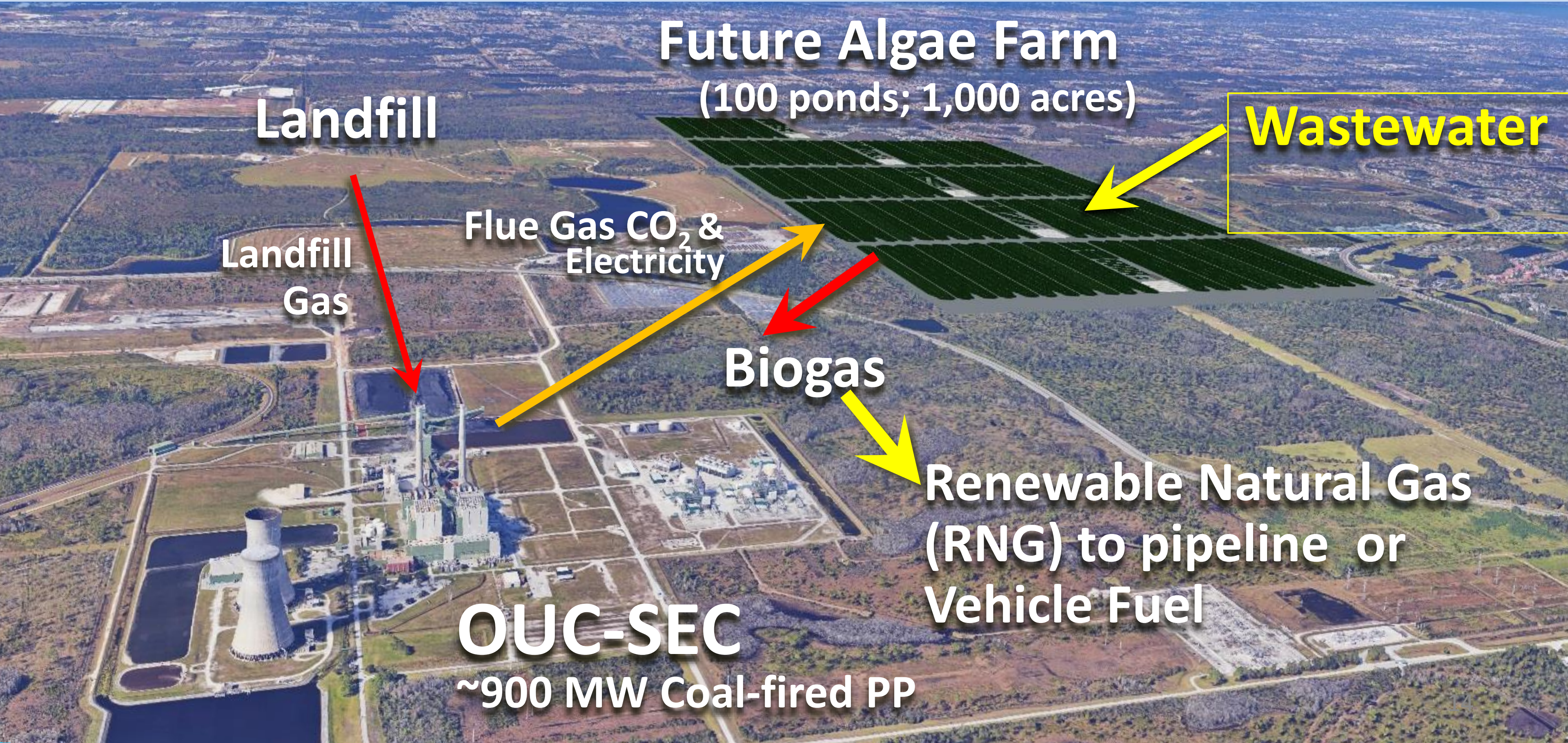
  Case 1 (Budget Period 1) Biogas production from algal biomass to replace coal for maximum CO_2 utilization and mitigation, and

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

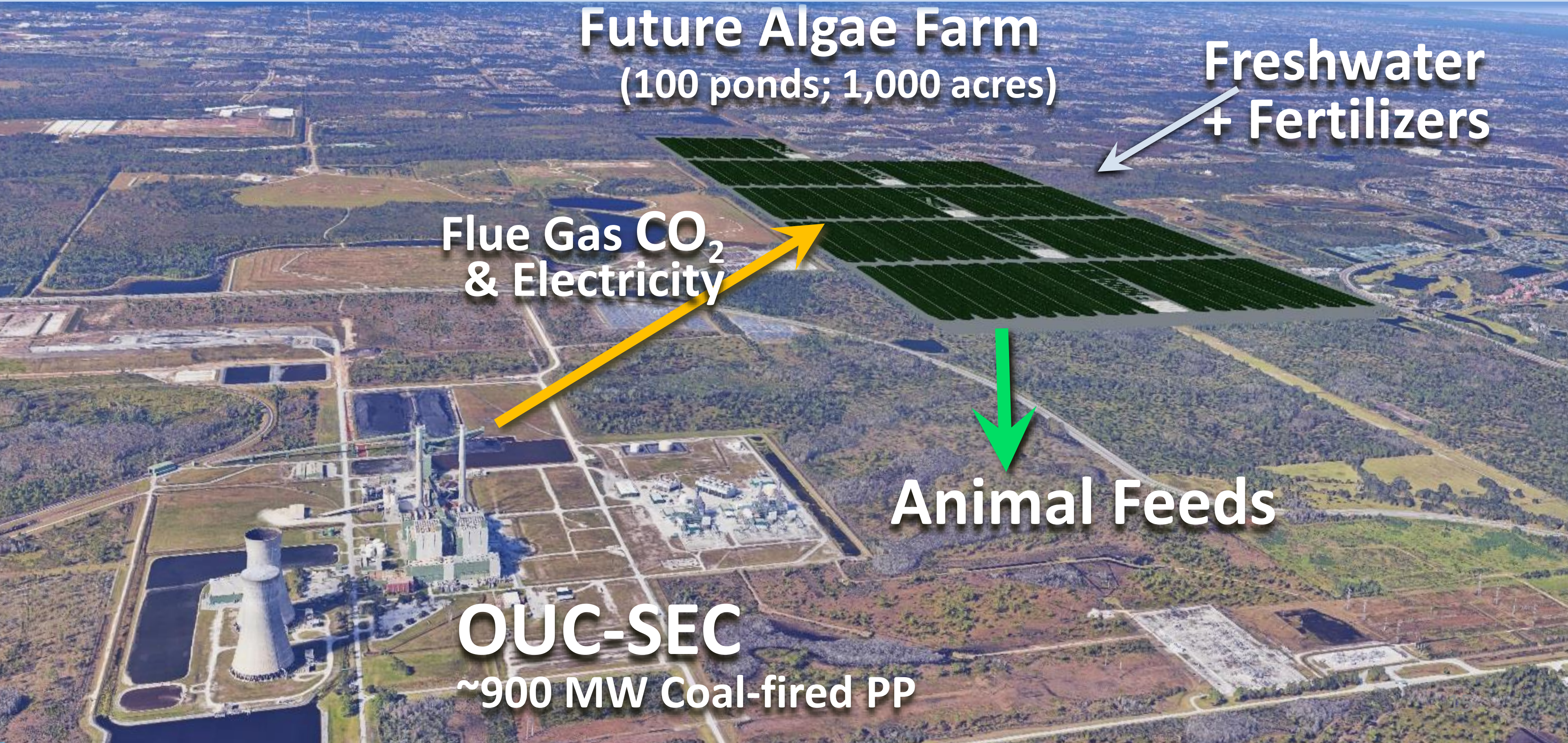
Case 1 (1st Yr): Flue-gas CO2→Algae → biogas → power plant



Case 1b. (1st Yr) Flue gas CO2→Algae → biogas→ RNG



Case 2. Algae → animal feed production (2nd year, current)



DOE-NETL DE-FE0026490: Overall Project Objectives "Microalgae Commodities from Coal Plant Flue Gas CO2"

- **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:

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

- **Secondary Objective: experimental work at OUC-SEC and UF to demonstrate biomass production using flue gas CO2 and native algal strains for conversion to biogas and animal feed**

Experimental Work

Experimental work: growth of native algae in raceway ponds at OUC (with flue gas) and U. Florida (for biogas)

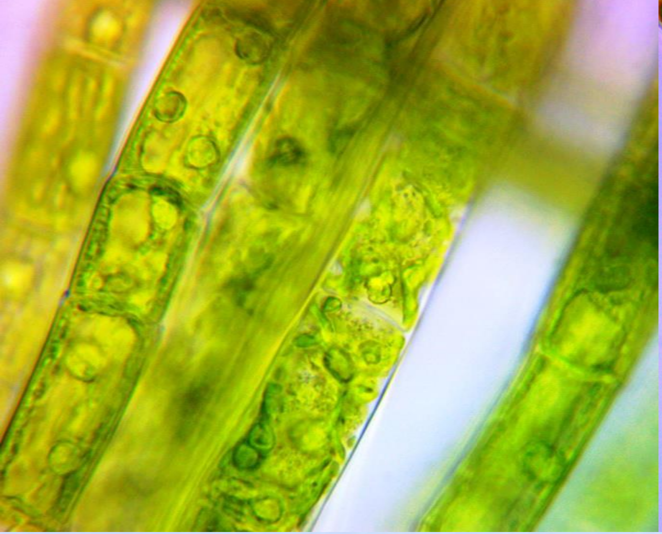
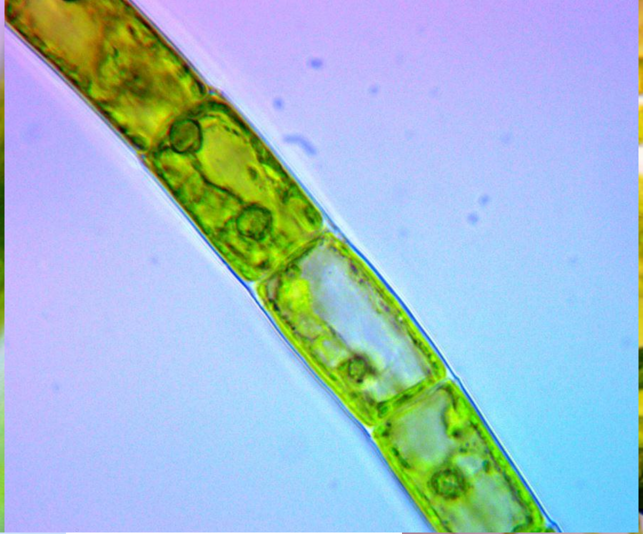
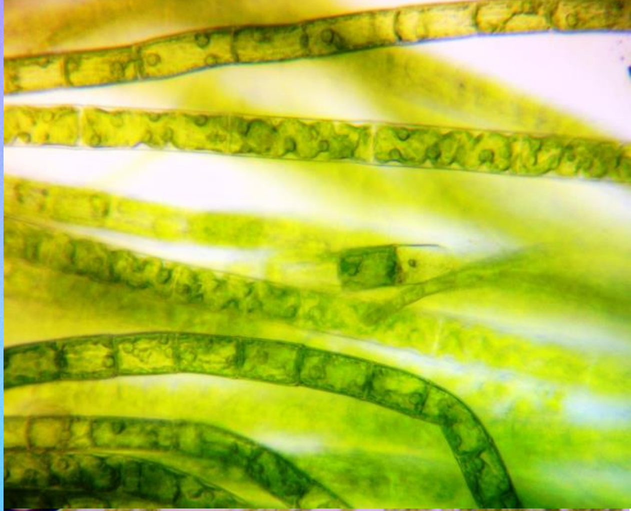
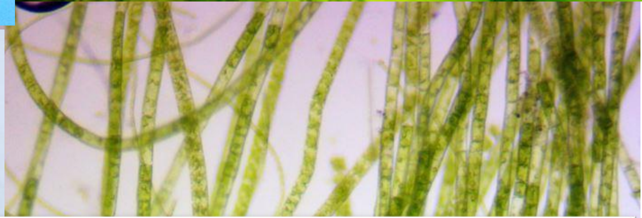
- Four 3.5-m^2 raceways at each location
- At OUC and UF, determine seasonal productivities of natural algal strains/consortia, optimize hydraulic residence times, analyze biochemical composition, effects of flue gas contaminants.
- At OUC, compare flue gas to pure CO_2.
- At UF, algal cultivation, biogas (methane) yields.

Experimental Algae Raceway™ Ponds fabricated by MicroBio Engineering Inc. (MBE) and installed /operated at/by OUC-SEC

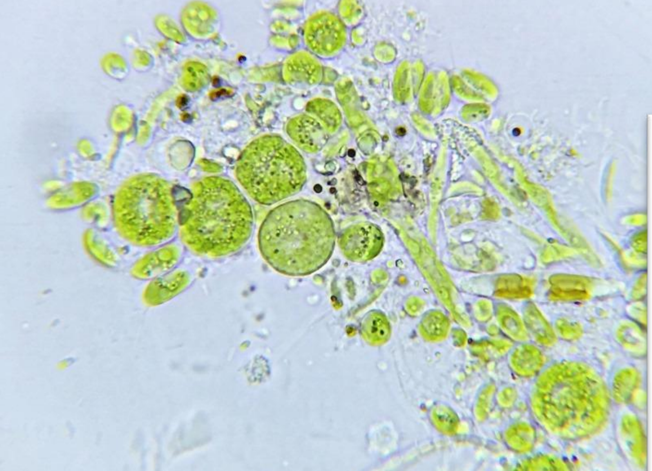
Flue gas from scrubbers to condensate traps to pump to pilot ponds

Eric Costello

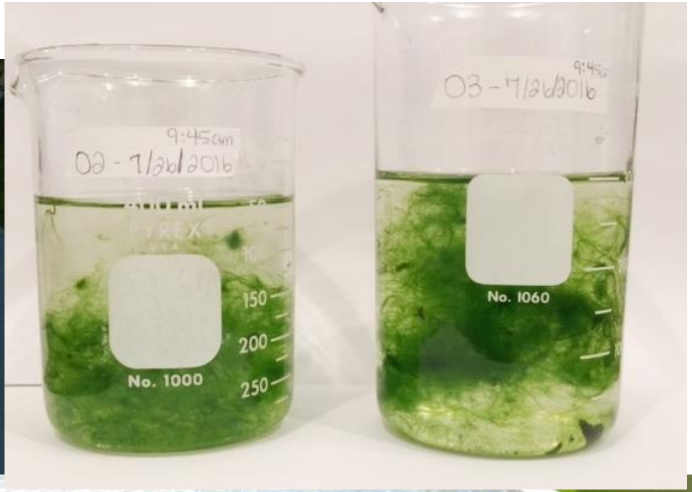
Flue gas from scrubbers to condensate traps to pump to pilot ponds with CO_2 consumed by algae

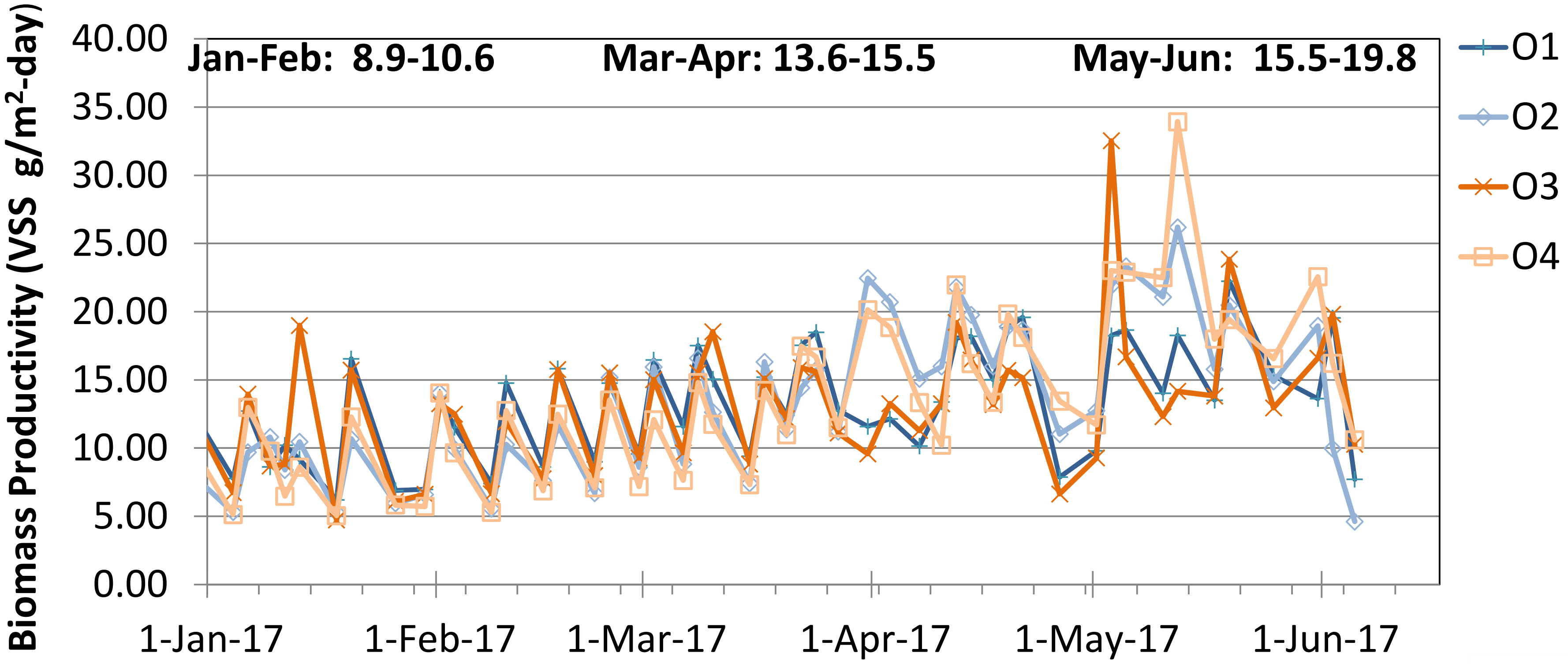
Microalgae observed at OUC-SEC Ponds


Filamentous algae dominated the OUC Ponds, which allows for easy harvesting of the biomass.



Jan-Jun 2017 productivity averaged 14 g/m^2-d at OUC. Weeks of rain are the major detriment to productivity.



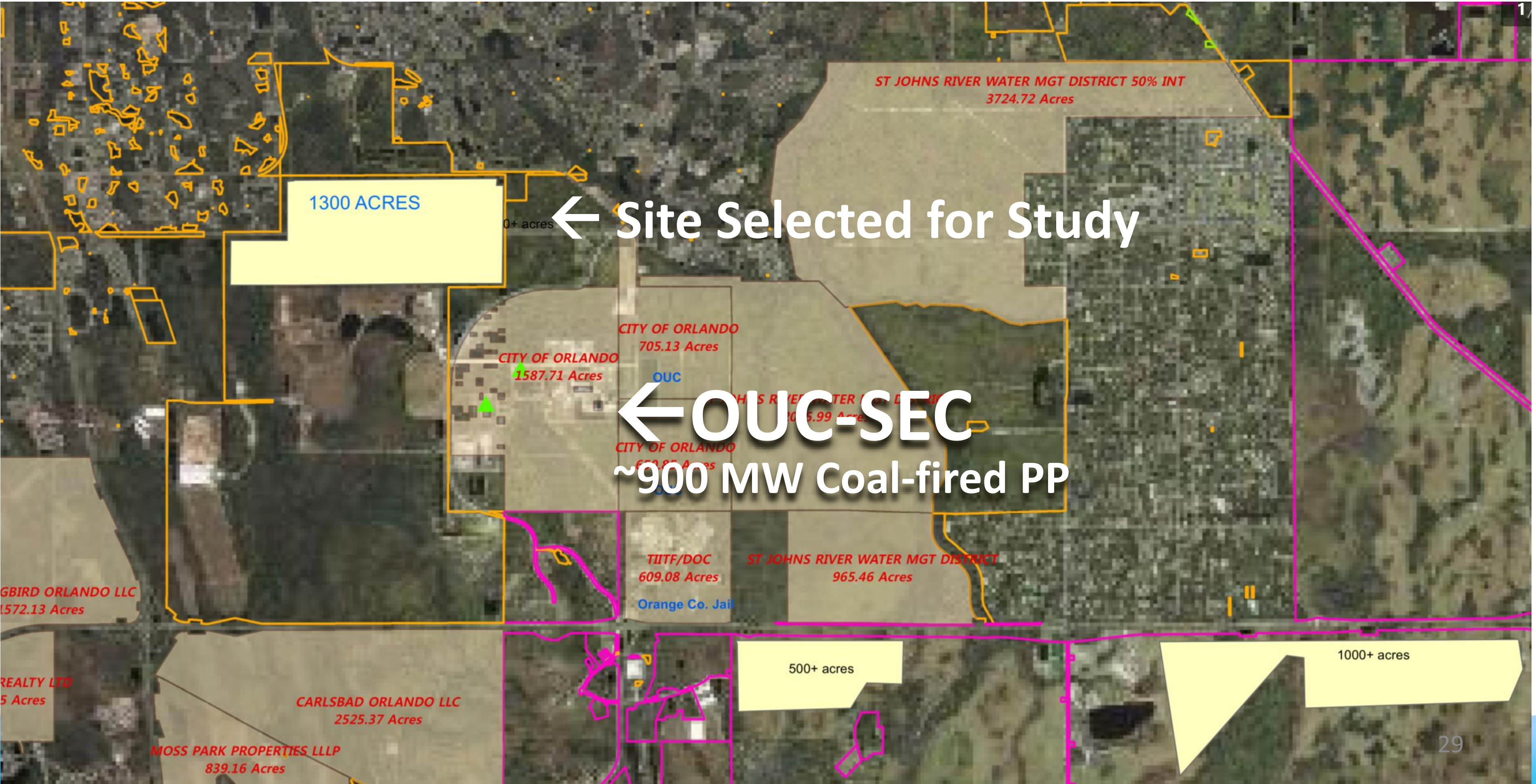
Pilot ponds at University of Florida - Gainesville

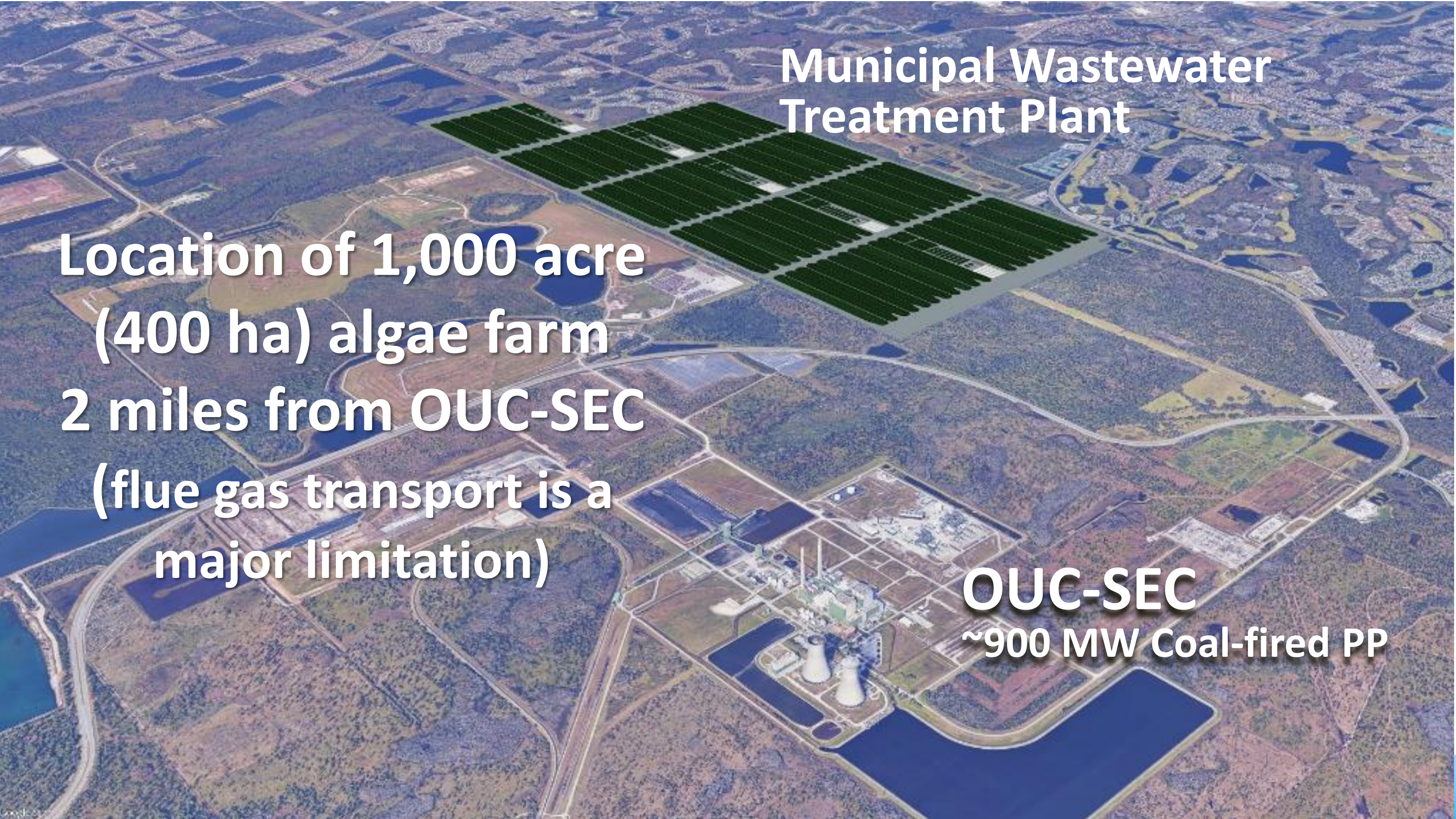
At UF: Bioflocculating cultures that settle

SEC and UF algae anaerobically digested at UF to determine CH_4 yield

Site Selection for TEA/LCA at OUC-SEC for a commercial 1,000 acre system

Potential Sites near OUC-SEC




Municipal Wastewater
Treatment Plant
Location of 1,000 acre
(400 ha) algae farm
2 miles from OUC-SEC
(flue gas transport is a
major limitation)
OUC-SEC
~900 MW Coal-fired PP

Flue Gas Conditioning and Transfer Operating Parameters

Parameter	Value
Operating Temperature/ Pressure	70 F / 40 psig
Flue Gas Composition	**11% CO_2**, balance N_2, some O_2 (trace contaminants, NO_x, etc.)
Avg. Flow (15 g/m^2-day biomass)	17,000 cfm @ 68 F and 1 atm/day
Peak hourly Flow (summer)	122,000 cfm @ 68 F and 1 atm/hr

Case 1 TEA/LCA .
Power Plant Flue Gas CO2 → Algae → Biogas

1a. Flue Gas CO2 → Algal Biomass → Biogas → Replace Coal

1b. Flue Gas CO2 → Algal Biomass → Biogas→ RNG

Case 1a

Flue Gas CO2 → Algae Ponds → Biogas → Replace Coal

Farm Size: 400 ha (1,000 acres), 2 miles to OUC SEC Power Plant

Productivity*: 33 g afdw/m^2-day (annual average)*

50 g afdw/m^2-day (peak daily, in summer)*

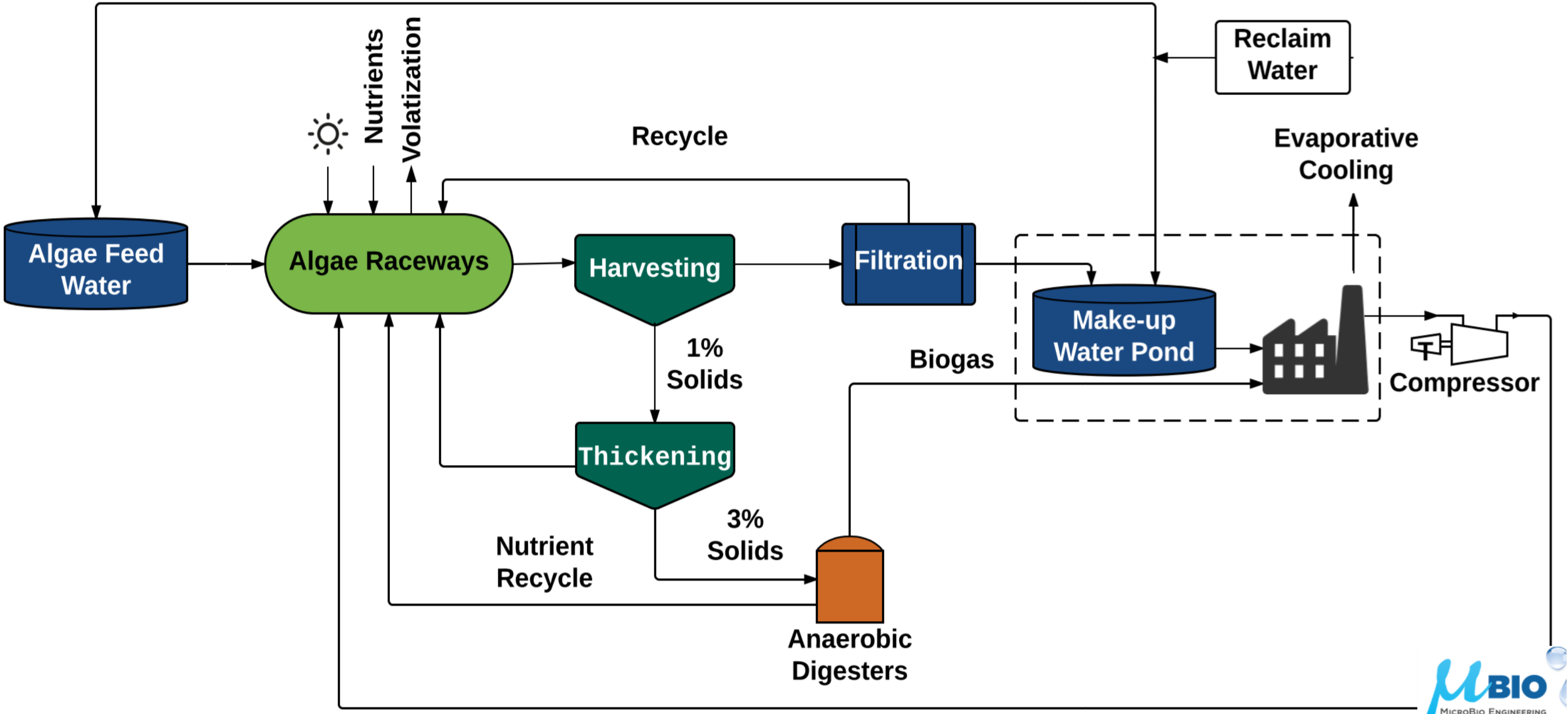
Flue Gas CO2 Efficiency of Capture into Algal Biomass: 55%

Make-up Water Source: Municipal Wastewater Treatment Plant

Make-up Water Rate: 38,700 m^3/d (10 MGD)

***High productivity to be achieved by complete recycling of biogas digester effluents**

Case 1a – Algae derived biogas to replace coal in PP.



Case 1a. Biogas to Power Plant Carbon Utilization Summary

Description	Value	Units
Coal Electricity Carbon Intensity	286.5	g CO_2eq/MJe
Total Biogas HHV Energy Generated	492,138,000	MJ/yr
Total Biogas Electricity Generated	99,122,000	MJe/yr
Total Reduction in GHG Emissions	28,400	CO_2eq mt/yr
Percent of OUC-SEC Emissions	0.7%	

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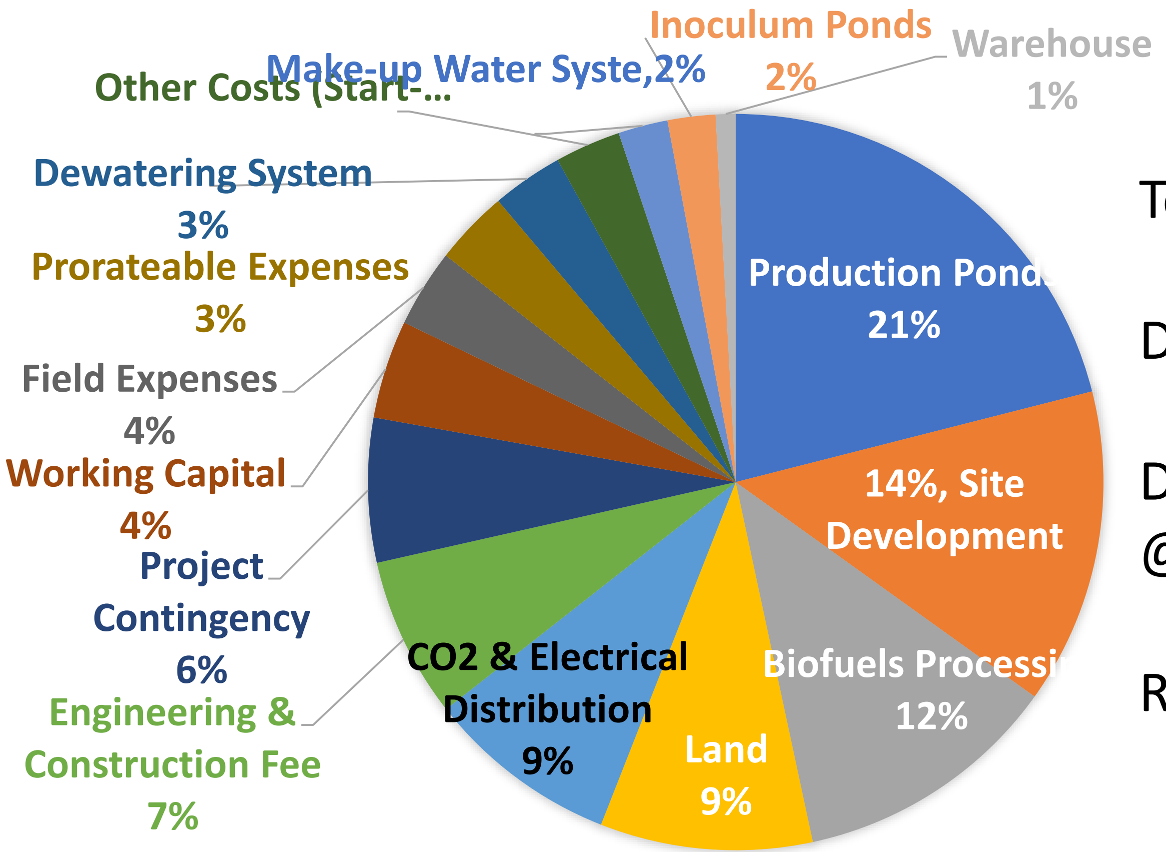
Case 1a - Biogas to Power Plant: CAPEX Summary



Total Investment: **$132, million**

Debt:Equity financing **80:20%**

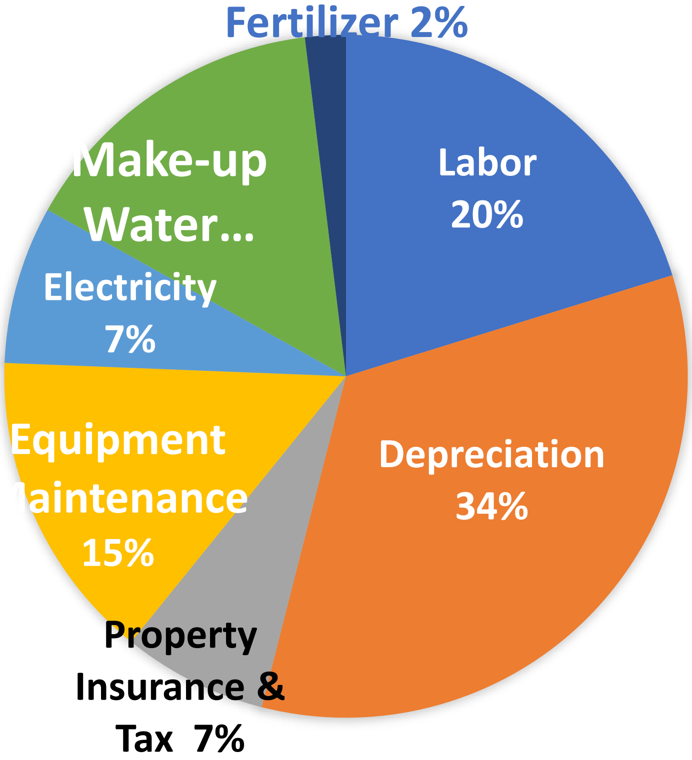
Debt (Bond Payment, 20 yr @5%): **$8,500,000 /yr**

ROI (15%): **$3,900,000 /yr**

MicroBio Engineering

MicroBio Engineering Inc engineering designs, cost analysis. Financial parameters: Davis et al 2016, NREL

Case 1a -Biogas to Power Plant: OPEX Summary



CAPEX (Bond + Equity) **$12,400 000 /yr**

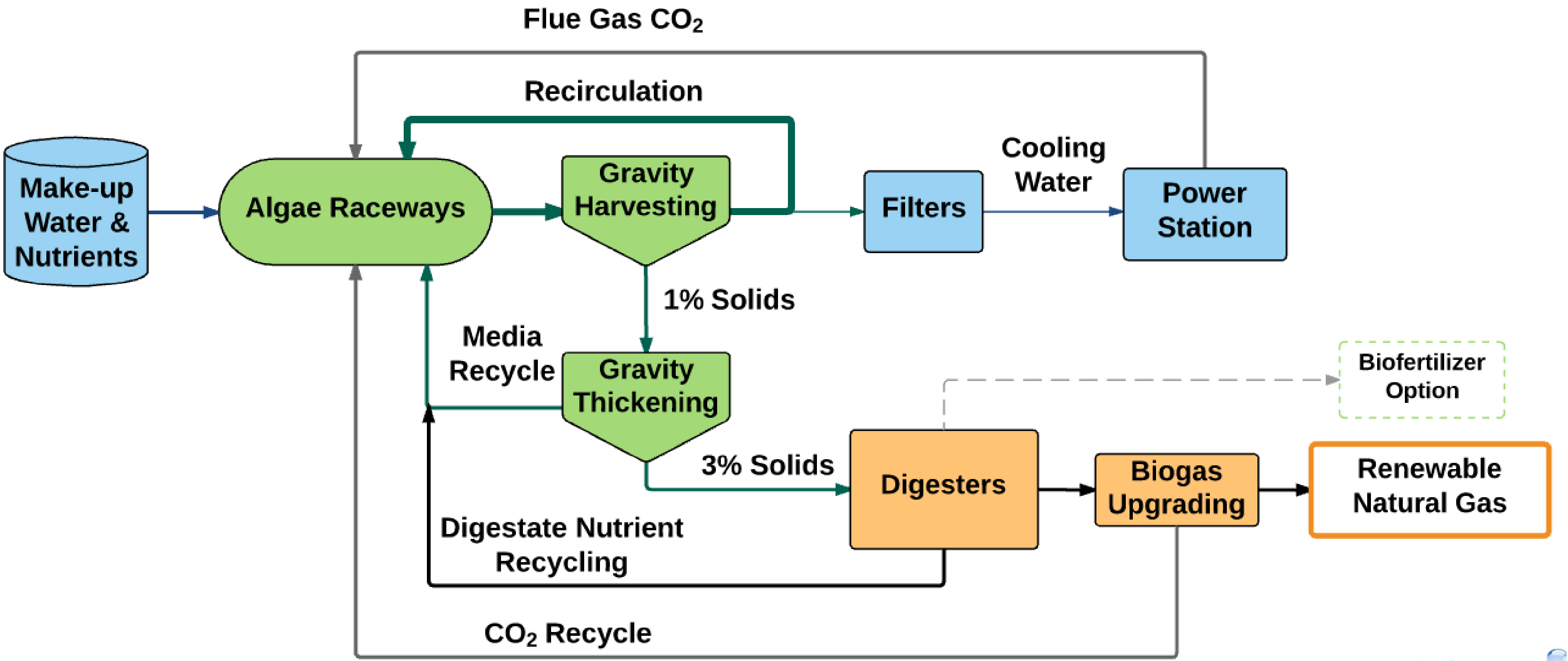
Operating Costs: **$11,600,000 /yr**

Biogas @ $2 /mmBtu: **$933,000 /yr**

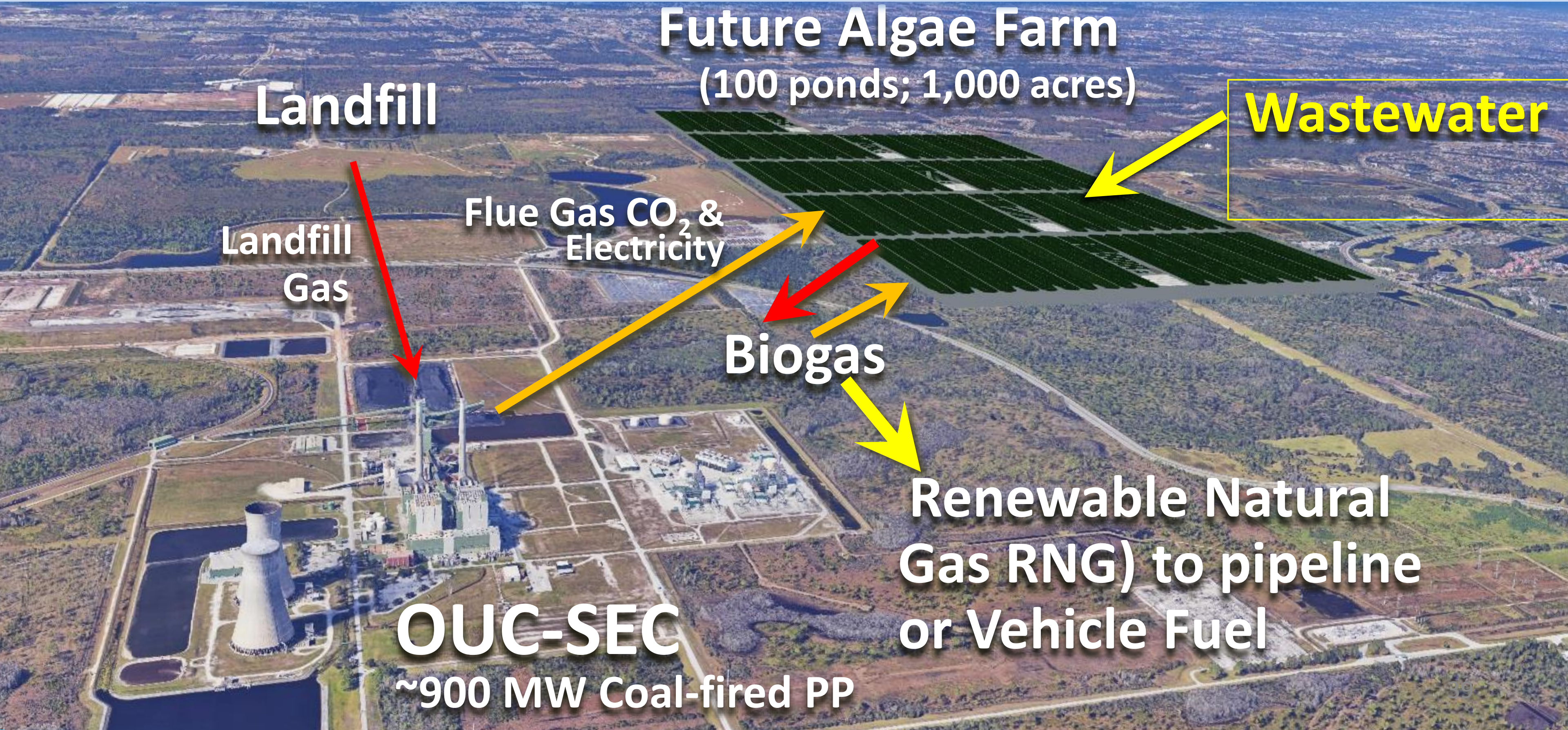
CO_2 Mitigation Cost (biogas to replace coal): **$816 /mt CO2**

MicroBio Engineering Inc engineering designs, cost analysis. Financial parameters: Davis et al 2016, NREL

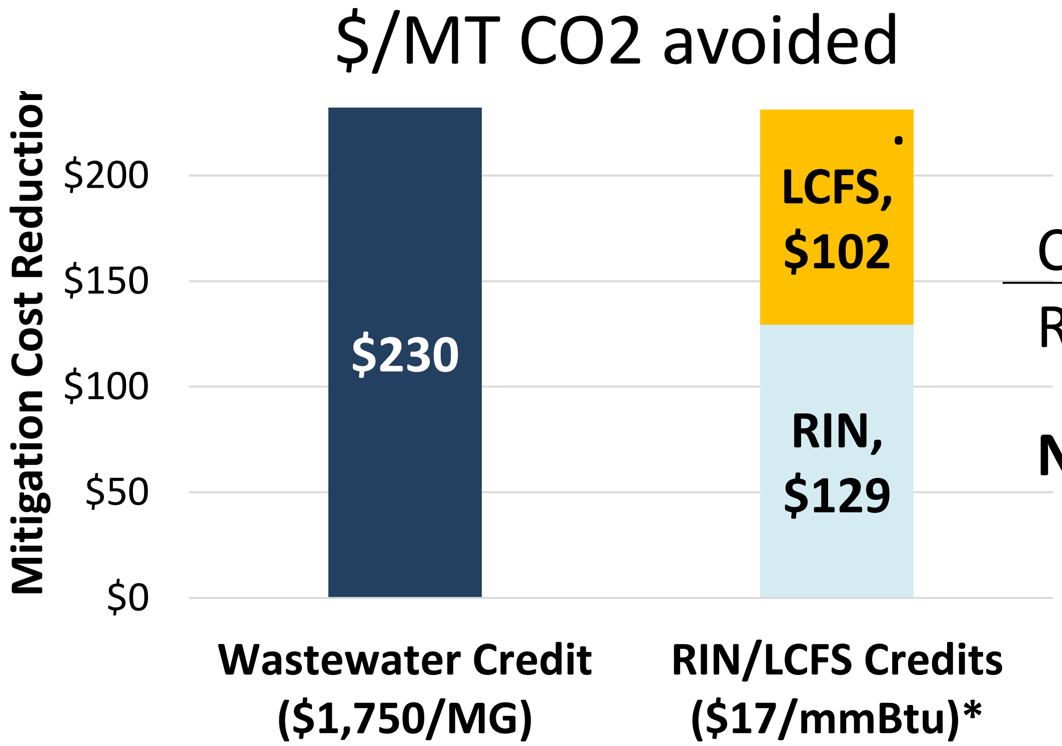
Case 1b: Production of Renewable Natural Gas (RNG)



Case 1b. Alternative Process: Algae WWT → biogas→ RNG



Case 1b - RNG Alternative: Biogas production + Wastewater Treatment (**12 million gallons/day**); remove CO_2 from biogas to upgrade to RNG ('Renewable Natural Gas') for pipelines, vehicles.



Costs = $816 / mt CO2

Revenues = $461 / mt CO2

NET : $355 /mt CO2 avoided

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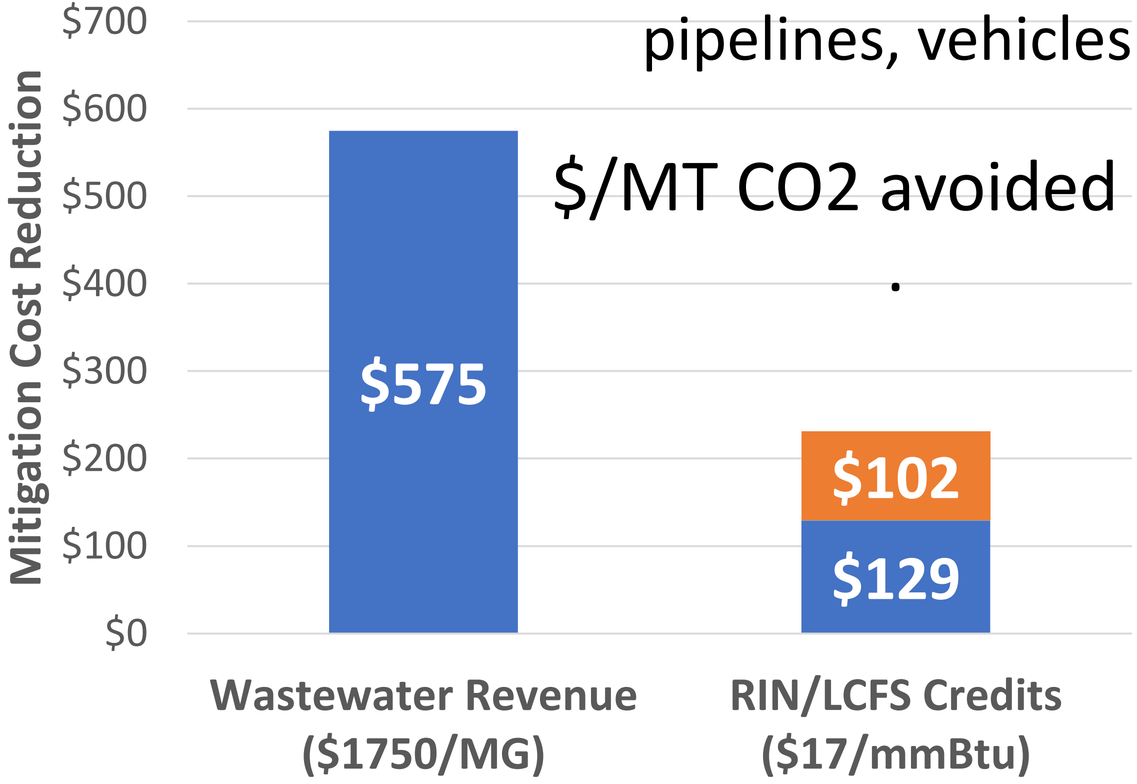
Case 1b - RNG Alternative: Biogas production + Wastewater Treatment (**increase to 30 million gallons/day**); remove CO2 from biogas to upgrade to RNG ('Renewable Natural Gas') for pipelines, vehicles.



Costs $816/mt CO2

Revenues: $806/mt CO2

Net : $10 /mt of CO2 emissions avoided

Case 2. Animal Feed Case

MicroBio Engineering

Animal Feed Case Design Parameters

Farm Size: 400 ha

Productivity: 18 g/m^2*d (annual avg.) 35 g/m^2–day (peak)

Flue Gas Source: OUC-SEC CFPP

Distance to Farm: 2 miles

Flue Gas CO_2 Uptake Efficiency: 55%

Water Source: Municipal Wastewater Treatment Plant

Blowdown Rate: 5%

Make-up Water Rate: 38,700 m^3/d (10 MGD)

MicroBio Engineering

LCA Modeling Parameters

LCA Model Type: Long-term Consequential (Co-product allocation)

LCIA Method: US EPA TRACI v2.1

Modeling Software: openLCA

Data Sources:

- OUC-SEC specific flue gas characteristics
- Orange County reclaimed water characteristics
- Mass balance of algae, MBE ESPE model
- Ecoinvent US regional utilities (electricity, natural gas)

Soybean and Algae Feed Characteristics

	Soybeans*	Freshwater Algae*
Protein	42%	45%
Oil	22%	20%
Carbohydrates & Other Organics	36%	35%
Nitrogen Content	6.7%	7.2%

*Ash free dry weight basis, based on Soybeans 13% moisture and 4% ash content.

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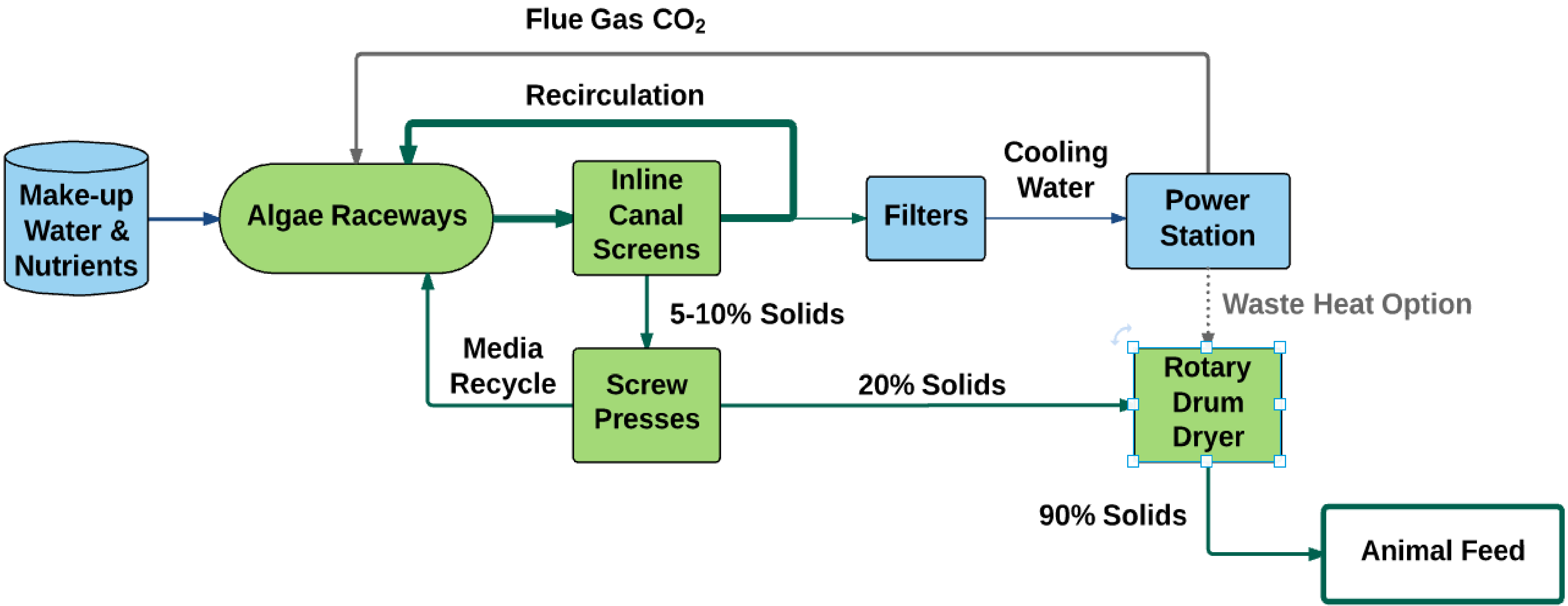
Feed Content Essential Amino Acids

	Soybeans[1]	Freshwater Algae[2]	
Isoleucine	4.54	4.54	
Leucine	7.78	8.56	
Lysine	6.38	6.97	
Methionine + Cystine	2.59	2.73	
Phenylalanine + Tyrosine	8.08	8.63	
Threonine	3.86	4.96	
Valine	4.80	5.82	

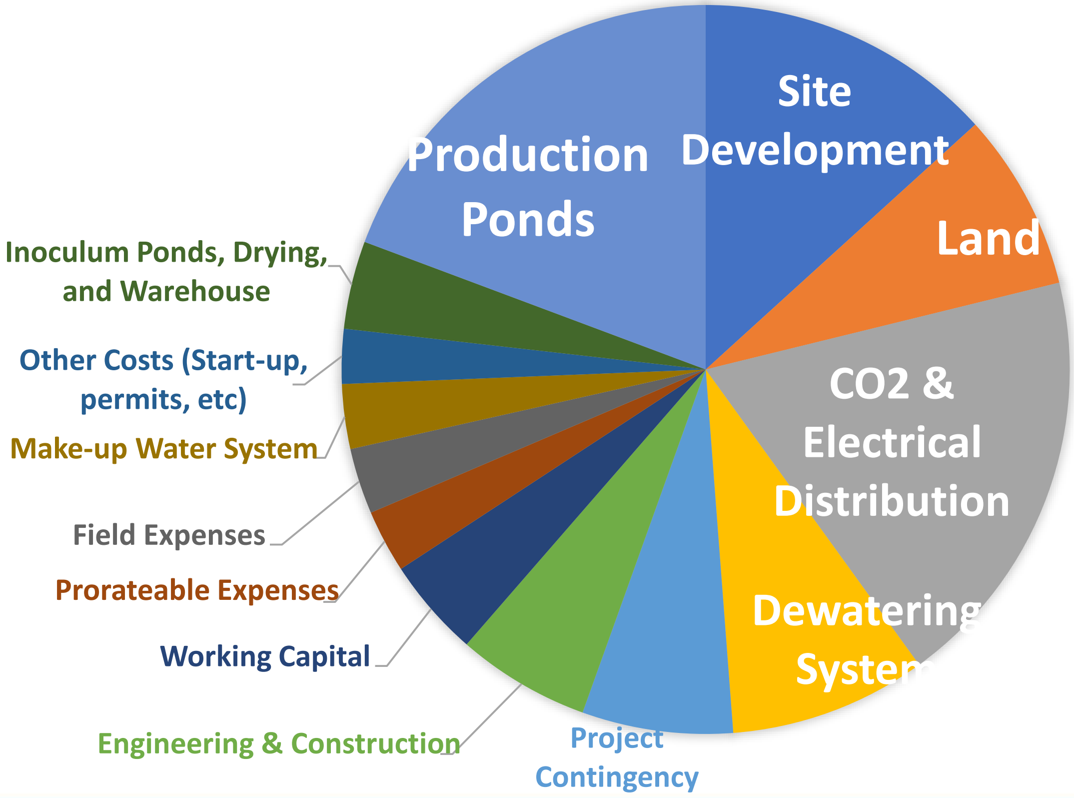
[1] Berk, Z. "Chapter 1 The Soybean." *Technology of Production of Edible Flours and Protein Products from Soybeans*. Rome: Food and Agriculture Organization of the United Nations, 1992.

[2] Boyd, C. E. (1973). Amino Acid Composition of Freshwater Algae. Arch Hydrobiol vol. 72:1-9.

Filamentous Microalgae Animal Feed Production



Animal Feed Financial Summary CAPEX



Total Capital Investment: **$125,000,000**

Percent financed by debt: **80%**

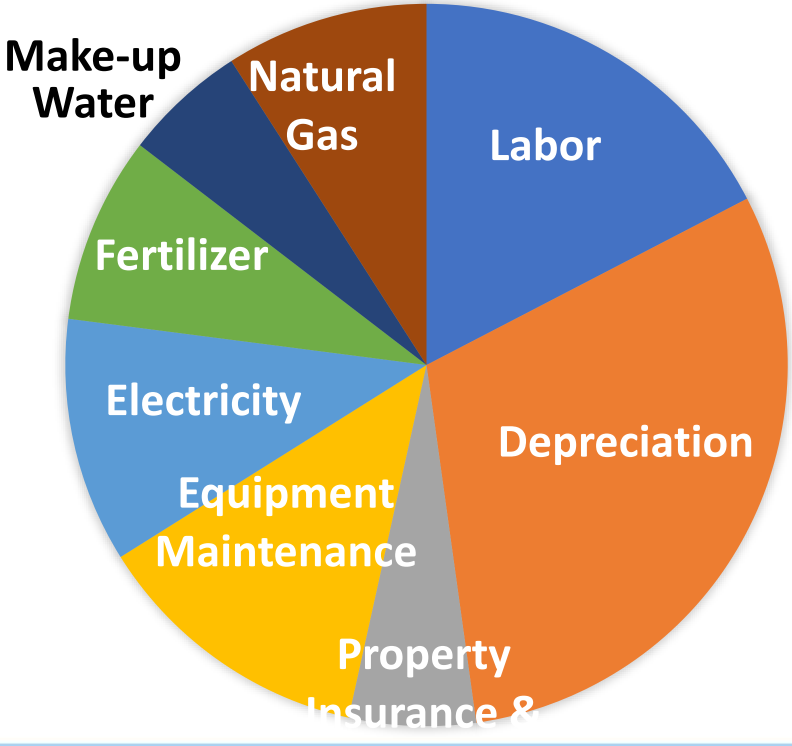
Percent Financed by equity:**20%**

Bond Payment (20 yr pond at 5%): = **$8,030,000 /yr**

Return on Equity (15%) = **$3,750,000 /yr**

MicroBio Engineering Inc engineering designs, cost analysis. Financial parameters: Davis et al 2016, NREL

Animal Feed Financial Summary OPEX



Bond Repayment:
$8,500,000 /yr

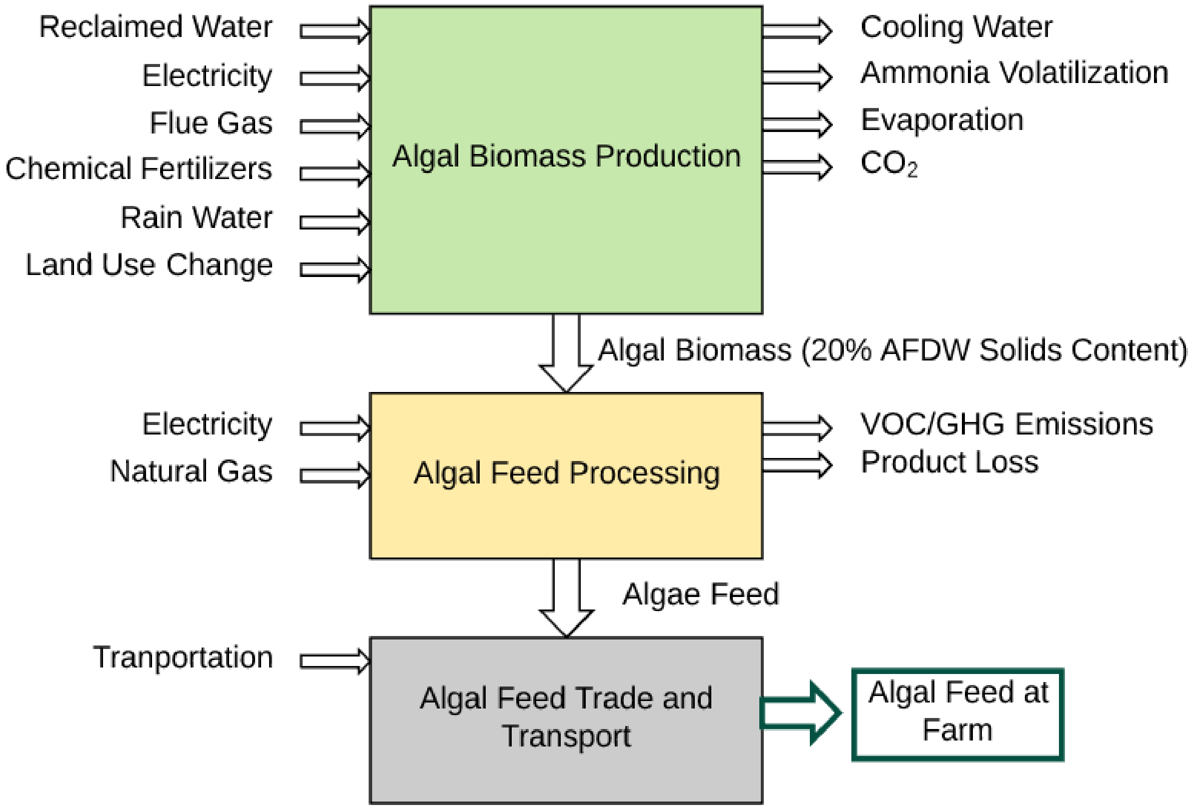
Return on Equity:
$3,900,000 /yr

Operating Costs:
$11,600,000 /yr

Animal Feed Selling Price **$965/mt**

MicroBio Engineering Inc engineering designs, cost analysis. Financial parameters: Davis et al 2016 NREL

LCA (life Cycle Assessment) for Animal Feeds



LCA Model Type: Long-term Consequential (Co-products)

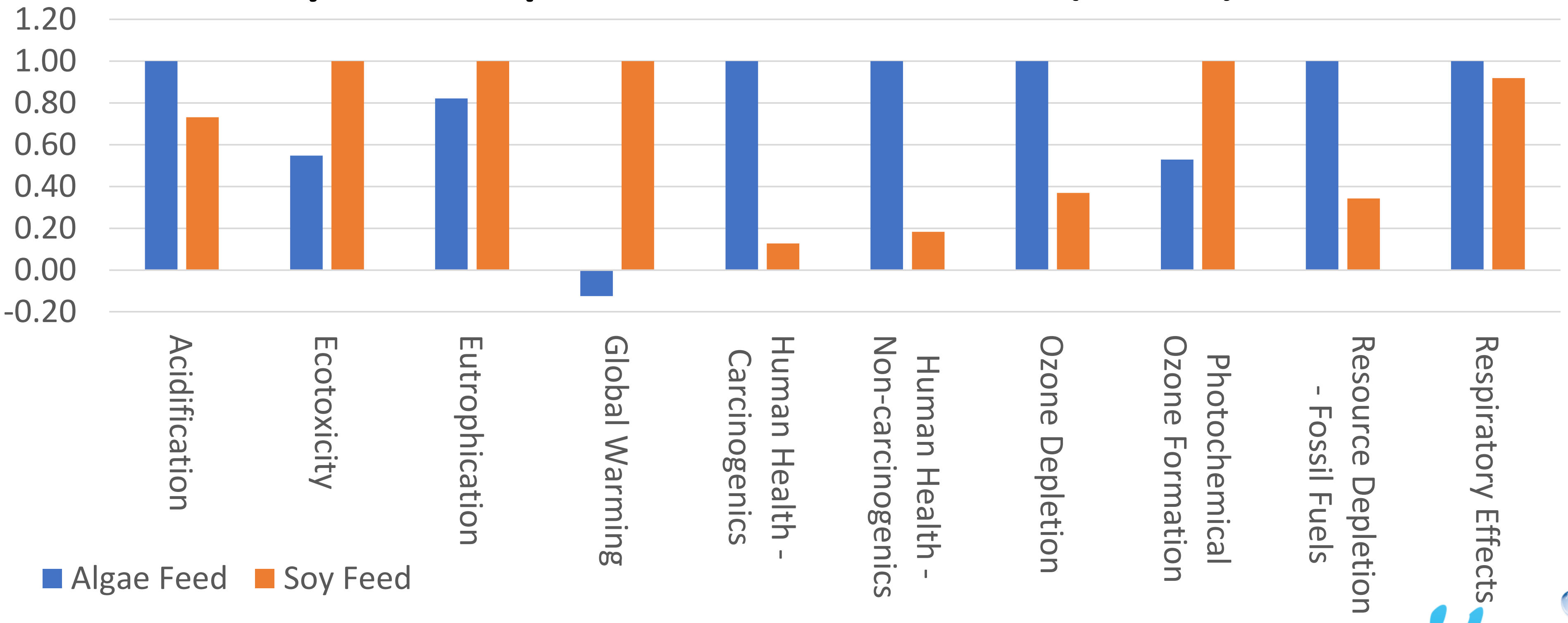
LCIA Method: US EPA TRACI v2.1

Modeling Software: openLCA

Data Inputs:

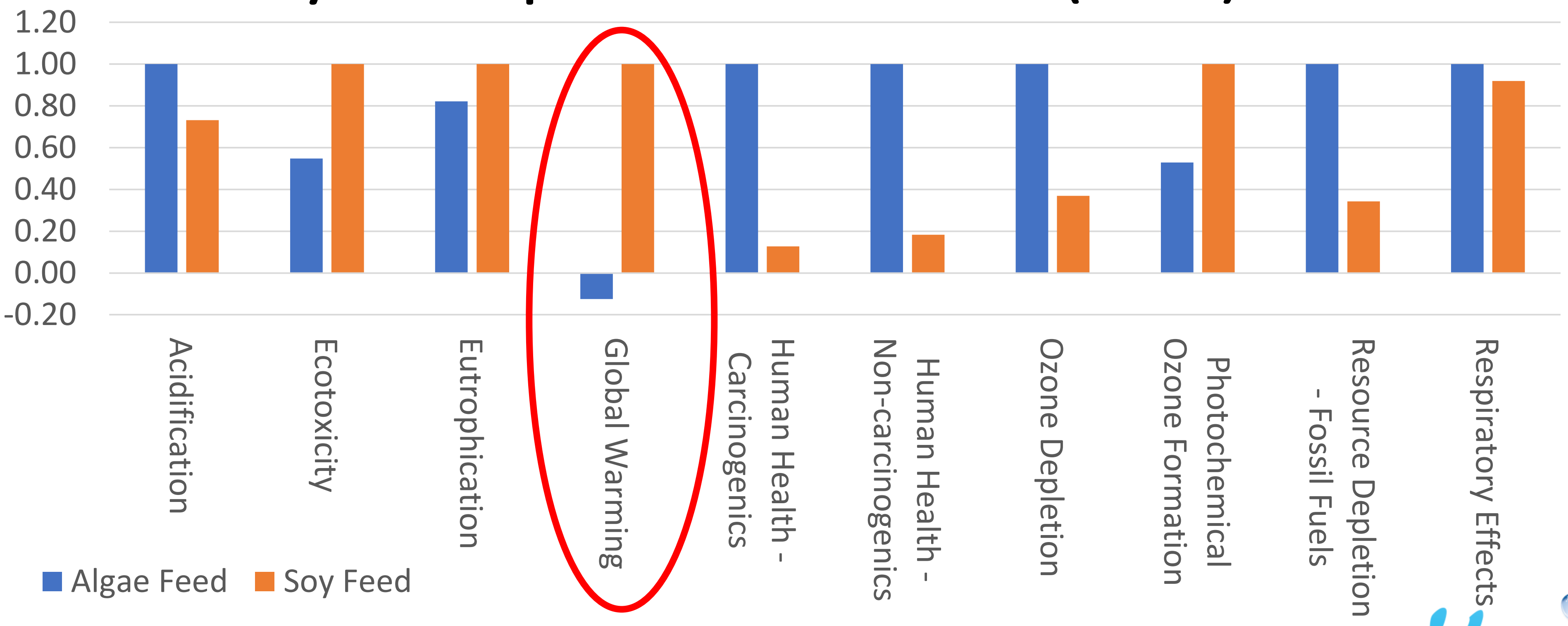
- OUC-SEC flue gas composition
- WWT Plant reclaimed water
- MicroBio Engineering Inc. TEA Algae TEA /Engineering Model
- Ecoinvent US regional utilities (electricity, natural gas)

Life Cycle Impact Assessment (LCIA) Results



Microalgae feed much lower GHG emissions than soybeans

Life Cycle Impact Assessment (LCIA) Results



Microalgae feed much lower GHG emissions than soybeans

Animal Feed Carbon Utilization Summary

Description	Value	Units
Global Warming Potential of Algae Feed	-0.473	kg CO2-eq/kg
Fraction of Carbon in Algal Biomass	47%	
Mass of Algal Feed Produced	26,300	mt/yr
CO2 Captured in Feed	45,300	mt/yr
OUC-SEC CO2 Annual Emissions	4,200,000	mt/yr
Percent of CO2 Utilized	1.1%	

Conclusions

- 400 ha (1000 acres) of algae production required for economics of scale.   Utilizes ~1% of a 900 MW CFPP
- **Case 1.   Biogas production.**
  - Wastewater treatment revenue is necessary to make carbon utilization economically feasible
  - Economics also depend on carbon markets (LCFS and RIN credits)
- **Case 2. Animal Feeds**
  - Algae feed similar nutritionally to soybean (protein, energy)
  - LCA for GHG highly favorable for microalgae feeds vs. soybeans
  - Project algae feed selling price: **$965/mt,** (~3 X soybeans)

Future Developments in Microalgae CO2 Utilization

- Technological advances required to achieve projected low CAPEX/OPEX
- Select/ improve algal strains for productivity, stability, composition, etc.
- Develop Wastewater/Flue gas CO2 Utilization/ Biogas to RNG Process
- Valorize algal nutritional components for higher value animal feeds.
- Commercialization in niche markets (biofertilizers, specialty feeds, etc.)

PROPOSED NEXT OUC-MBE PROJECT PHASE:

Expand ponds at OUC-SEC to four x 43 m2

Scale-up of filamentous algae at OUC-SEC

Flue gas CO2 utilization for algal feeds, fuels

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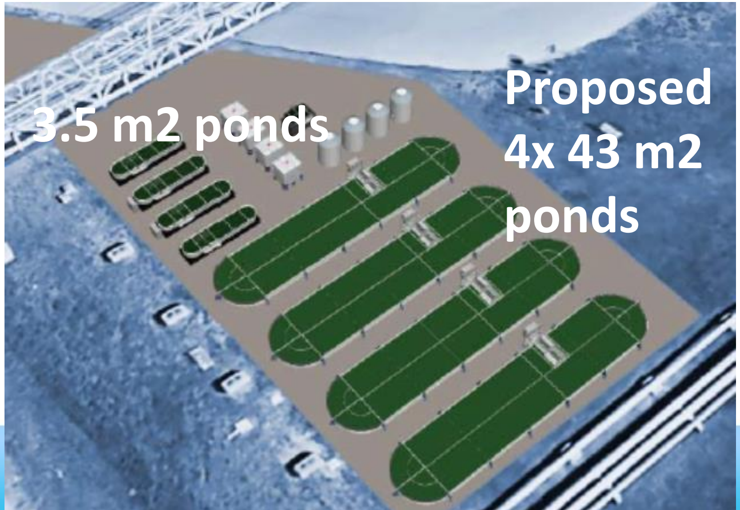

Thanks to all participants in this project at MicroBio Engineering Inc., the Orlando Utilities Commission, U. of Florida, Arizona State Univ., Scripps Institution of Oceanography, Lifecycle Associates and SFA Pacific Inc. And DOE-FE - NETL and OUC for financial support.

Questions?