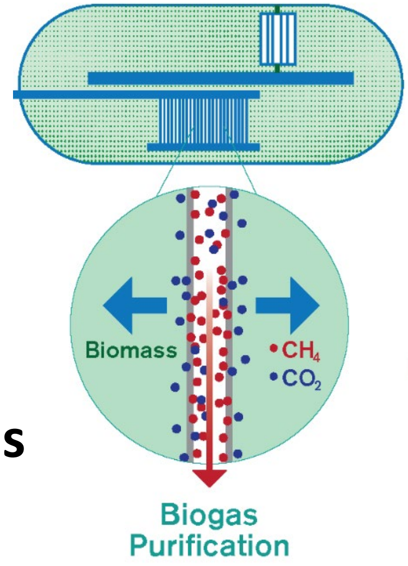
DOE Bioenergy Technologies Office (BETO) 2021 Project Peer Review

Membrane Carbonation (MC) for 100% Efficient Delivery of Industrial CO_2 Gases

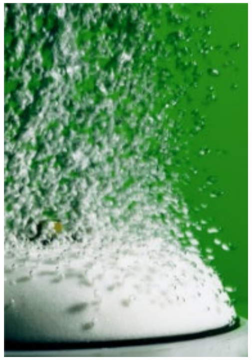


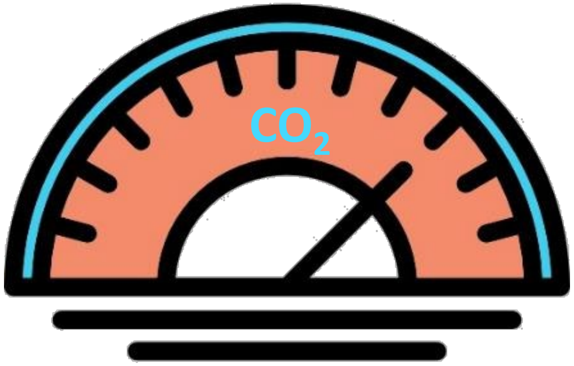
Technology Area Session: **Advanced Algal Systems**
Date: **March 23, 2021**
Principal Investigator: **Bruce Rittmann**
Organization: **Arizona State University**

This presentation does not contain any proprietary, confidential, or otherwise restricted information

Bottlenecks in CO_2 Delivery to Algae

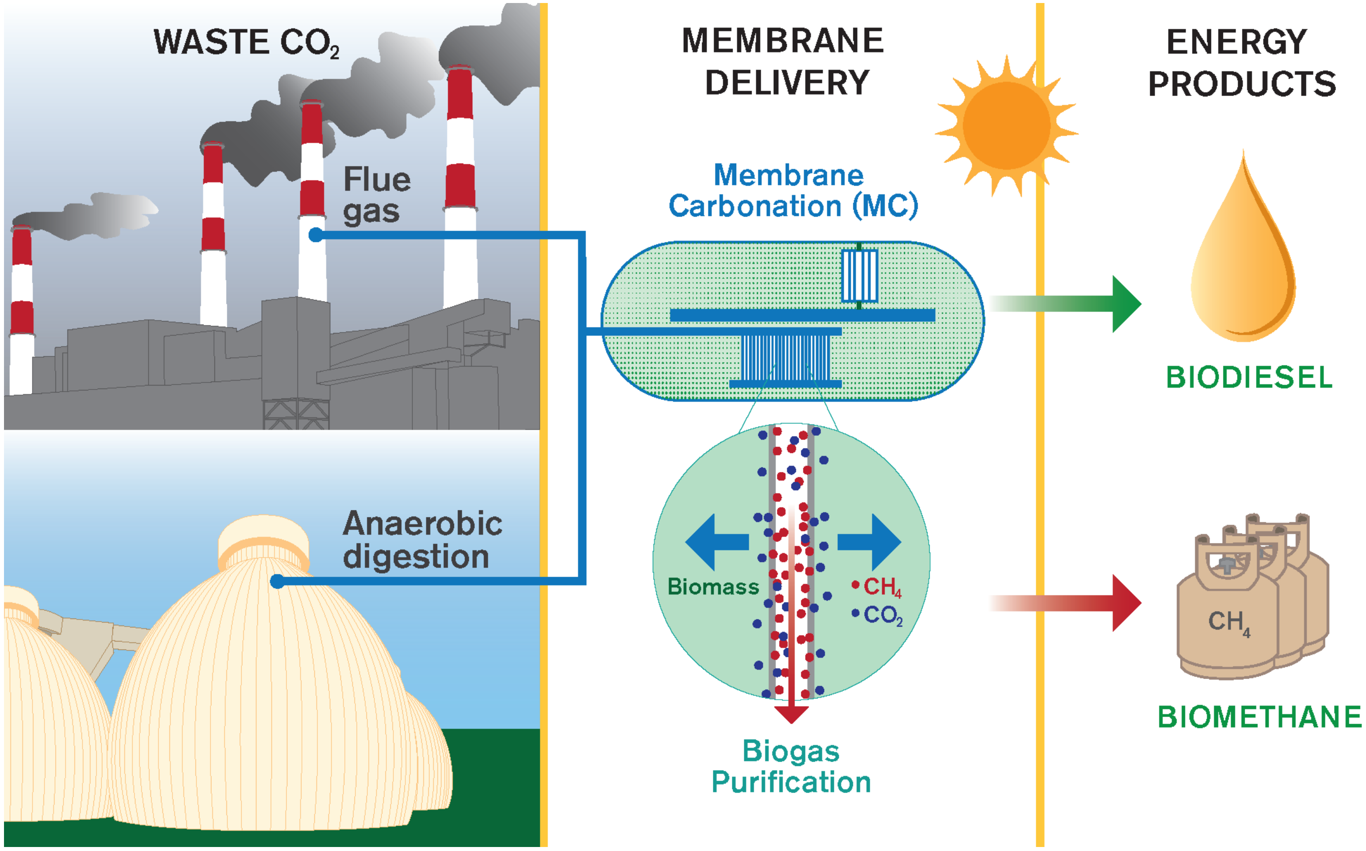
- Growth is limited by ~400 ppm CO_2 in atmosphere
- Trucked CO_2 is expensive, ≥ $200/ton
- Industrial CO_2 gas varies widely by source
- Sparging CO_2 can release 60-80% back to atmosphere
- Industrial waste gas may have contaminants
- Industrial waste gas may have other valuable components





Project Overview

- **Goal:** Outdoor demonstration of MC using biogas, flue gas with > 25% improvement in carbon utilization efficiency (CUE) over sparging

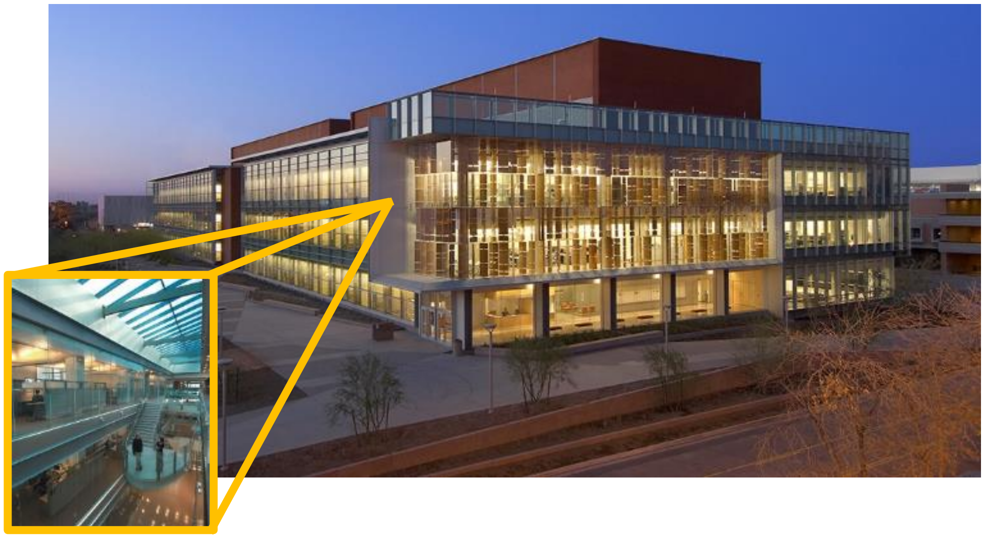


Benefits

- Efficient CO_2 capture into biomass from a wide range of sources
- CO_2 selectively removed to increase value of residual gas (e.g., CH_4)
- Bubble-free CO_2 delivery: >90% to media, >70% to biomass

Arizona State University

Biodesign Institute



ISTB-5

AzCATI

External Partners

City of Mesa

Salt River Project

1 - Management

Management

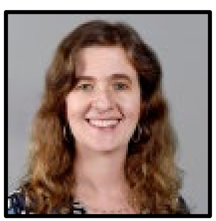
Bruce Rittmann
Principal Investigator

Justin Flory
Project Manager

Risks and Mitigation

- **Inert gas builds up:** use bleed valve to purge inert gases
- **Non-selective CO_2 transfer in mixed gas:** mathematical modeling (Excel, COMSOL)
- **Not cost-effective or sustainable:** techno-economic and life-cycle modeling

Indoor cultivation and modeling



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co-PI

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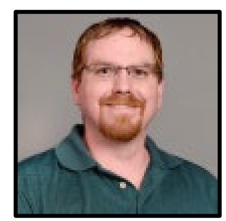
Michelle Young
Research Scientist

Zoe Frias
Undergrad student

Outdoor Cultivation

John McGowen
co-PI



Everett Eustance
Research Scientist

TEA and LCA

Robert Stirling
TEA

Jason Quinn
LCA

2 - Approach

Technical Approach

- **Abiotic evaluation** of synthetic gases with 5–80% CO_2 in mildly alkaline media, focused on flue gas [5, 14% CO_2], biogas [35% CO_2]
- **Biotic evaluation at lab scale** of synthetic flue gas and biogas. Include CH_4 and H_2S in biogas. Down select conditions for outdoors
- **Outdoor cultivation** of synthetic flue gas and biogas over multiple seasons, increasing complexity and scale (e.g., synthetic gas to raw biogas and 4-m^2 to 25-m^2 raceways)

- **Mathematical modeling** to track multiple gas components and optimize experimental conditions (Excel and COMSOL)
- **Techno-economic and life-cycle analyses** to guide research and assess economic and sustainability goals (renewable fuel standard)

Challenges

- **CO_2 off-gassing at pH < 8 reduces carbon utilization efficiency**
  - As this was significant, we are increasing pH in subsequent trials
- **Lower flux with flue gas**
  - Assessing impact with techno-economic and life-cycle modeling
- **Achieving ≥ 97% CH_4 purity** in effluent when cultivating with biogas
  - Observed O_2 back diffusion and CH_4 transfer to media

Go/No-Go @ Month 21 [actual results]

- Cultivation with initial MC delivering synthetic bio and flue gas for ≥ 3 weeks with ≥ 60% carbon transfer efficiency (CTE) **[86–97%]** and ≥ 50% carbon utilization efficiency (CUE) **[54–79%]** and ≥5% **[10%]** productivity over SOT and CH_4 purity of ≥ 80% **[83–95%]**
- MC process can deliver CO_2 for cultivation for ≤ $102/ton **[$73/ton]** assuming a cost of $50/ton CO_2 as described in the TechFin worksheet key performance parameter for Cost of CO_2

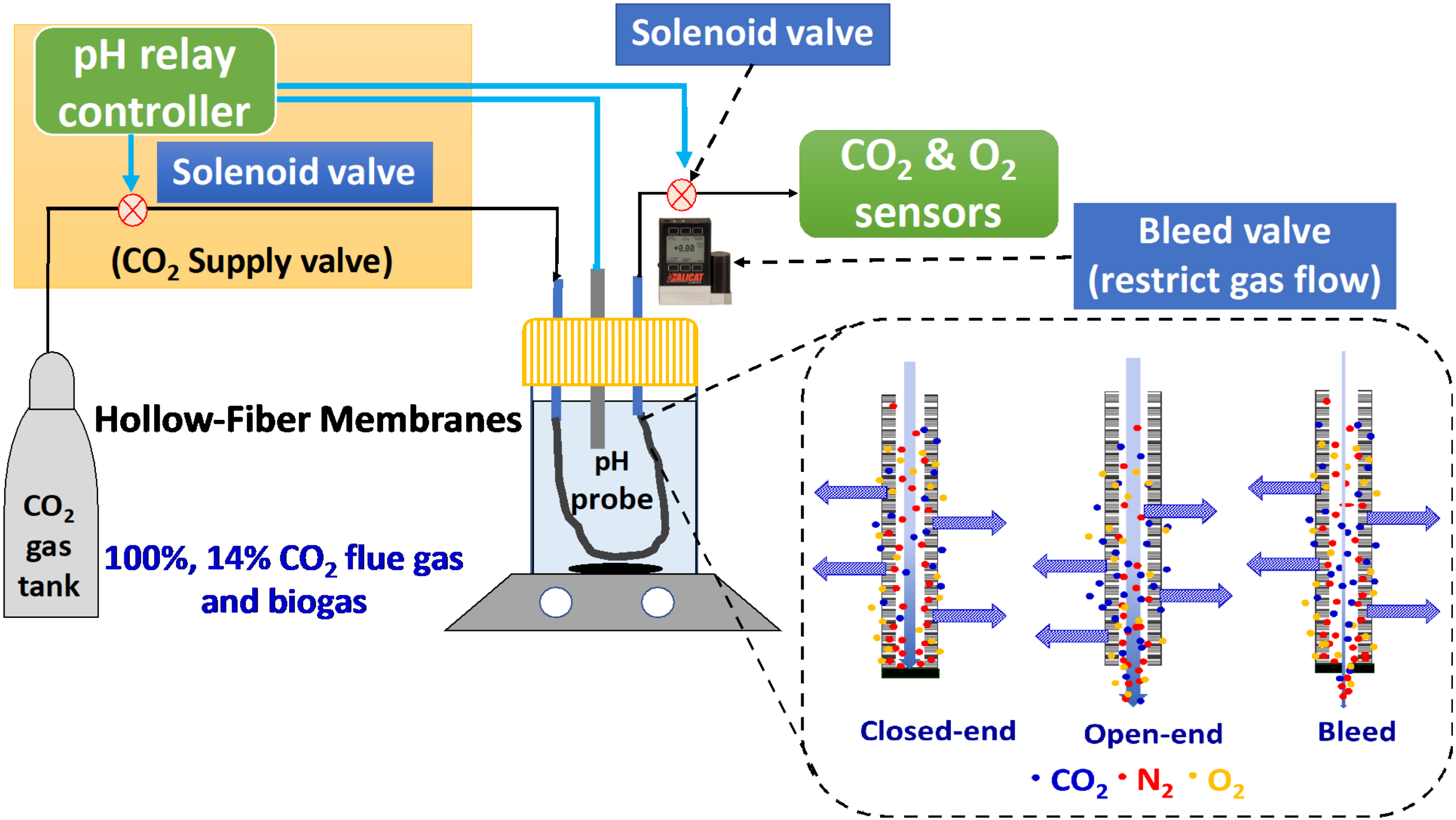
3 - Impacts

- **Improve carbon transfer and utilization efficiency (CTE/CUE)** from ≤ 40–50% and ≤ 30–50% for sparging to ≥ 90% and ≥ 80% with MC.
- **Increase CH_4 purity in biogas** from ~65% to ≥ 97% (i.e., biomethane)
- **Increase biomass productivity** by ≥ 10% over 2018 SOT
- **Savings vs sparging:** ≤ \$60/ton CO_2 delivered at \$50/ton CO_2 cost
- **Demonstrate feasibility** in 4 m^2 and 25 m^2 raceway ponds
- **On-site demo. at City of Mesa Wastewater Treatment Plant:**

  - Increase value of Mesa biogas to run generator or produce renewable fuels (vs flare)
  - Onsite water and nutrients
- **Peer-reviewed reports** to evaluate TEA, LCA and technical feasibility of MC
- **Patent** filed on Mar. 4, 2020

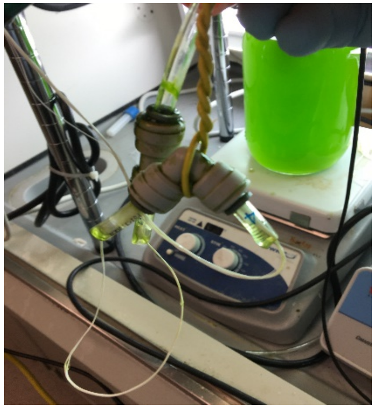
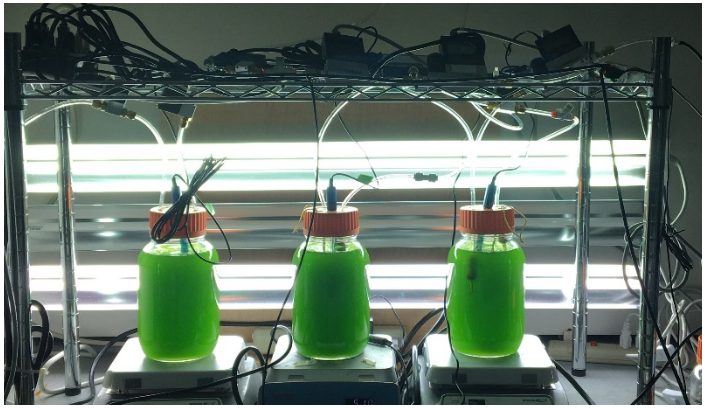
4 – Progress and Outcomes

CO_2 delivery approach for biotic and abiotic testing at lab scale

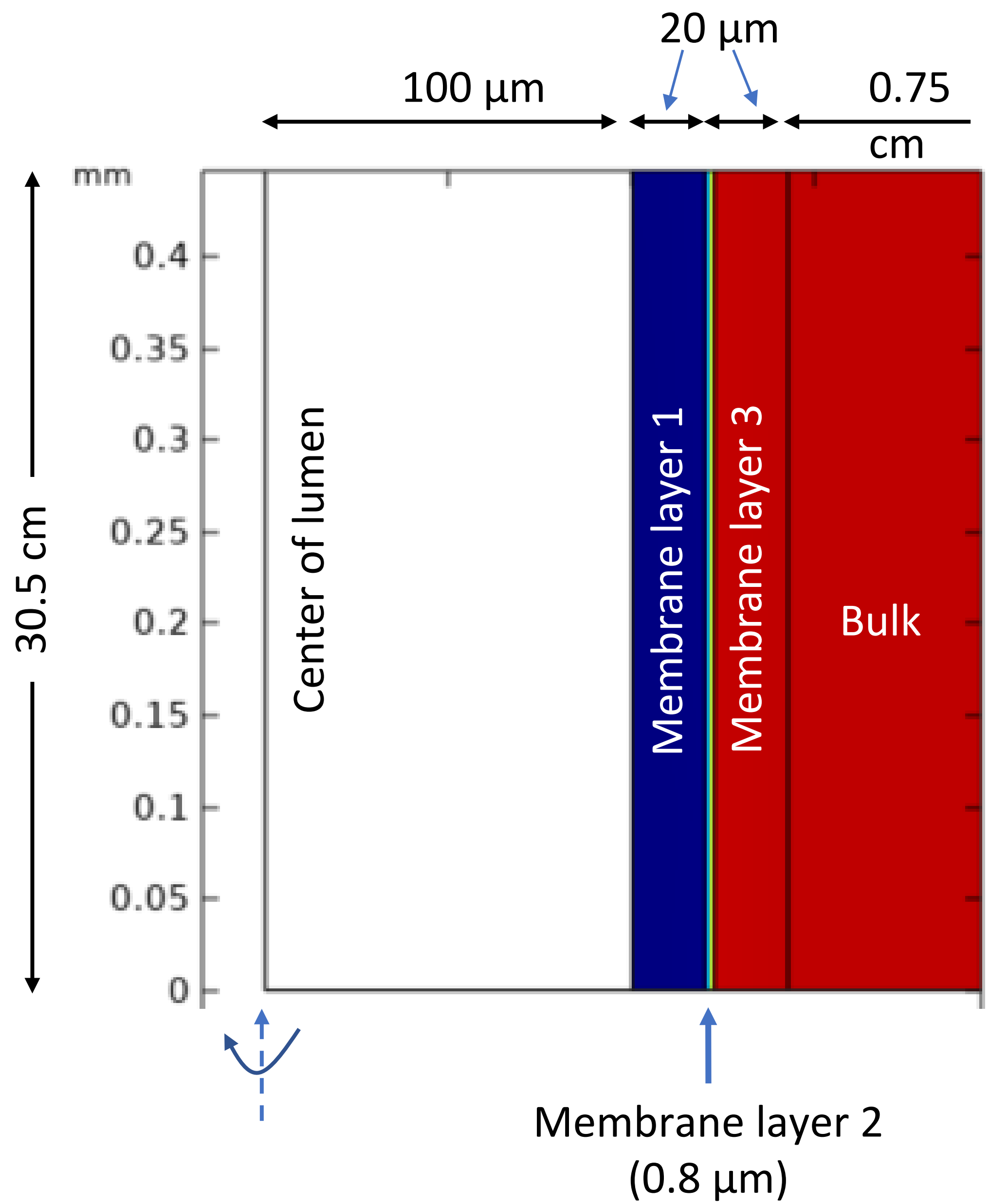


- **Abiotic evaluation at lab scale**
  - Flux target ≥ 250 g d^{-1} m^{-2} (fiber) met for 14% flue gas and above
  - Increase flow restriction to achieve higher CTE

- **Biotic evaluation at lab scale**
  - **Productivity** with biogas and flue gas was similar to 100% CO_2
  - >97% **CTE** (transfer), 65–67% **CUE** (utilization)

Mathematical Modeling



- **Excel Model**
  - Mass balance
  - Inform fiber-module design
  - Validated, within <5% of experimental data

- **COMSOL Model**
  - Physical model of gas transfer
  - Encompasses more phenomena
  - Especially valuable to optimize biogas delivery

Outdoor Cultivation

4.2 m^2 raceways at AzCATI

MC module

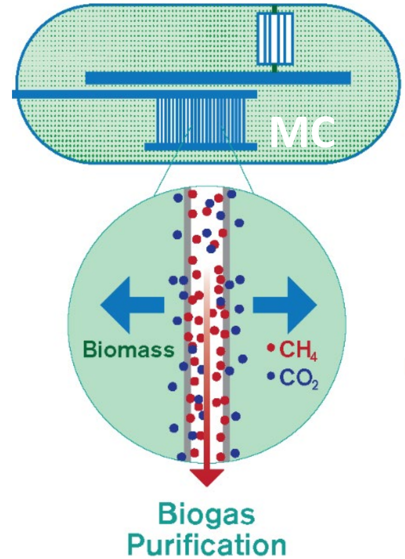
- ***Picochlorum celery*** (Pico) cultivated > 3 weeks with synthetic flue gas, biogas, and 100% CO_2 at pH 7.0 and 7.75
- **CTE:** 86–98% vs 40–50% for sparging
- **CUE:** 54–79% vs 30–50% for sparging
- **Significant off-gassing** at pH 7.0 and 7.75, which is below equilibrium with air (pH ~8.2)
- **Biogas effluent CH_4 purity** 83–95%

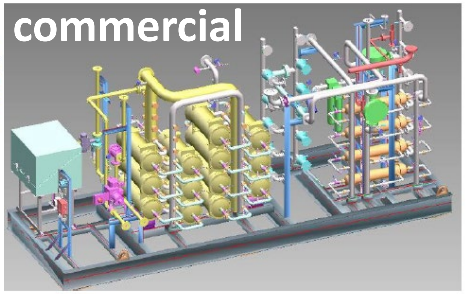
4 – Progress and Outcomes

Techno-economic analysis (TEA)

- Focus on **cost of delivering CO_2** with MC vs sparging
- **Key factors:** CO_2 supply cost and compression; and membrane flux ($g/m^2/d$), cost ($\$/m^2$), and lifetime.

Biogas CH_4 purification systems





- **MC shows cost savings**

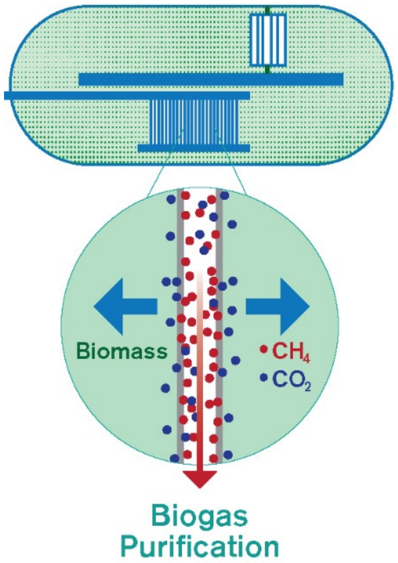
Life cycle analysis (LCA)

- Focus on **LCA of delivering CO_2** with MC vs sparging
- **Impact of MC insignificant** vs impacts of productivity, HTL yield, and dewatering.
- Greenhouse gas emissions: ~30 gCO_2-eq/MJ, which **meets the renewable fuel standard (RFS)** of < 45 $gCO_{2\text{-eq}}$/MJ
- Biogas **methane leaks insignificant** at expected levels

5 – Summary

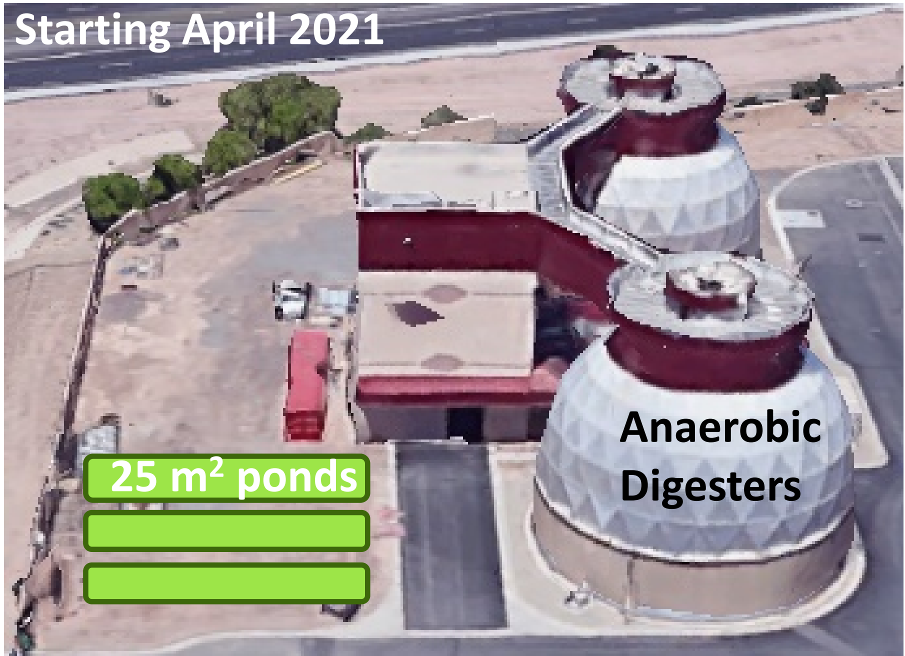
Membrane Carbonation for CO_2 delivery

- **CTE:** 86–98% vs 40–50% for sparging
  - Significant **cost savings** vs sparging; $73/ton
- **CUE:** 54–79% vs 30–50% for sparging
  - Significant **off-gassing** at pH < 8



- **Biogas effluent CH_4 purity** 83–95% (field values)
  - Significant **cost savings** vs commercial system
- COMSOL and Excel **models developed**
- Life-cycle analysis shows will meet **renewable fuels standard**

On-site demonstration at City of Mesa Wastewater Treatment Plant



Membrane Carbonation | ASU | Rittmann

Timeline

- Project start date: Jan 1, 2019
- Project end date: Dec. 31, 2021

	FY20 Costed	Total Award
DOE Funding	$712,766	$1,992,766
Project Cost Share	$341,545	$498,205

Project Partners

- Sustainability Science LLC (LCA)
- City of Mesa (biogas advisor/provider)
- Salt River Project (flue advisor)

Funding Mechanism

DE-FOA-0001908, Efficient Carbon Utilization in Algal Systems, 2018

Topic Area 1: CO2 Utilization Efficiency

Project Goal

Outdoor demonstration of membrane carbonation using biogas, flue gas with > 25% improvement in carbon utilization efficiency over sparging.

End of Project Milestones

- **Improve carbon transfer and utilization efficiency (CTE/CUE)** from 40–50% and 30–50% for sparging to ≥ 90% and ≥ 80% with MC
- **Increase CH_4 purity in biogas** from 65% to > 97% (i.e., biomethane)
- **Increase biomass productivity** by ≥ 10% over 2018 SOT
- ≤ \$60/ton CO_2 delivered (\$50/ton CO_2 cost); **>> savings vs sparging**
- Enable algal biofuels that meet the **renewable fuels standard**

Additional Slides

Responses to Reviewer Comments

2019 Peer Review Comments

- Poster presentation, no comments

Go / No-Go Review Highlights

- Monitor **membrane fouling** impact on performance: will complete in next trial
- **Purge condensed water** from ‘wet’ biogas: fiber ends are partially open, may need to periodically purge with dry gas
- **Optimize CUE beyond delivery**: will increase pH to around 8
- **Improve estimates for membrane lifetime**: membrane lifetime reduced from 10 years to 6 years for TEA
- **Update TEA / LCA models with experimental data**: process is ongoing and iterative; detailing product costs for first customer

Publications, Patents & Presentations

Publications

- Lai YS, Eustance E, Shesh T, Rittmann BE (2020) Enhanced carbon-transfer and -utilization efficiencies achieved using membrane carbonation with gas sources having a range of CO2 concentrations. Algal Research (52)
- Eustance E, Lai YS, Shesh T, Rittmann BE (2020) Improved CO_2 utilization efficiency using membrane carbonation in outdoor raceways. Algal Research (51)

Presentations

- Eustance E, Lai YS, Flory J, McGowen J, Rittmann, BE. Presentation at Algae Biomass Summit 2020, Virtual. Utilizing Membrane Carbonation with Synthetic Flue Gas and Biogas in Outdoor Raceways.
- Rittmann, B. E. (2020). Highly Efficient CO_2 Delivery from Industrial Sources. Presentation at the Algae Biomas Summit 2020 (August 20).
- Bruce Rittmann, “Opportunities in Microbial Bioenergy” Guest lecture, Arizona State University, Tempe, AZ. Nov. 12, 2019
- Bruce Rittmann, “Optimizing Microalgae Production by Delivering Sources of Concentrated CO_2” IWA Microalgae Conference, Vallodolid, Spain. July 2, 2019
- Bruce Rittmann, “Optimizing Microalgae Production by Delivering Sources of Concentrated CO_2” Gordon Research Conference on Photosynthesis, Newry, ME

Patents

- Methods and Systems for Membrane Carbonation; Everett Eustance, Bruce Rittmann, Yen-Jung Lai, Justin Flory, Tarun Shesh, Diana Calvo; Mar. 4, 2020. No. 16/809,384.