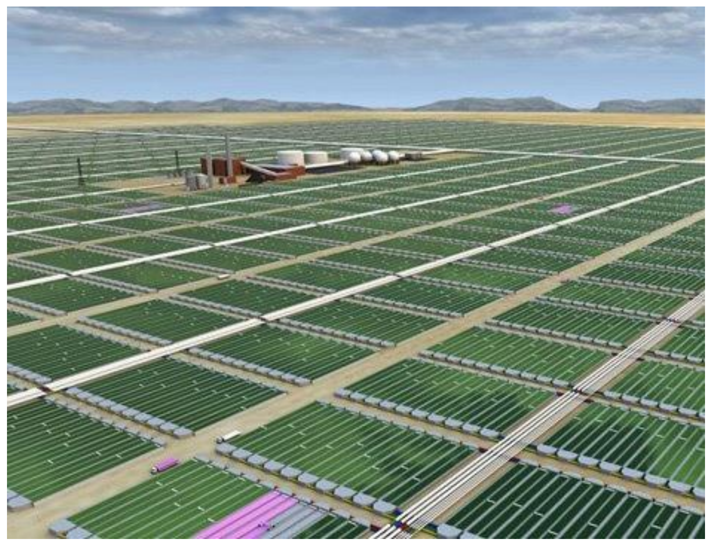
DOE Bioenergy Technologies Office (BETO) 2019 Project Peer Review

Atmospheric CO_2 Capture and Membrane Delivery (ACED)

CO_2



Large-scale algae cultivation (courtesy of Joule®)

Bruce Rittmann, Ph.D.

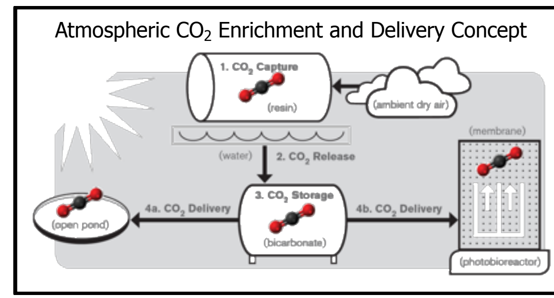
Principal Investigator, Arizona State University

March 4, 2019
Technology Session Area Review

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

ACED Goal Statement

- **Goal:** Design, build, and demonstrate a system for capturing and concentrating CO_2 from ambient air and delivering the CO_2 to microalgae.
- **Outcomes:**
  - Capture and concentrate CO_2 from ambient air
  - Store CO_2 in a carbonate brine
  - Extract, concentrate, and pressurize CO_2
  - Efficiently deliver CO_2 to grow microalgae
  - Outdoor algal cultivation for 1 month 1500-L pond with CO_2 captured from ambient air.



- **Relevance:** Provide a renewable, clean, and concentrated CO_2 stream to microalgae grown in any sunny location.

Quad Chart Overview

Timeline

- **Start:** 10/1/15 (Validation), 3/1/16 (Research)
- **Official End:** 8/1/18
- **Status:** 100% complete, Final Report submitted in December

Budget

	Total Costs Pre FY 19	FY 19 Costs (Project ended 9/30/18)
DOE Funded	$1,000,000	$0
Project Cost Share (Comp.)*	$251,991	$0

Barriers

- **Technical Barriers**
  - Atmospheric **CO_2 Capture** and Concentration
  - Efficient **CO_2 delivery** and utilization
- **MYPP Technical Targets**
  - **CO_2 Utilization:** 90%
  - **CO_2 + Nutrient Cost:** $120 / ton AFDW (2022)

Objective

Develop a system for concentrating CO_2 from ambient air and delivering the CO_2 to microalgae.

End of Project Goal

CO_2 delivery: >90% into media, >70% into biomass

1 – Project Overview

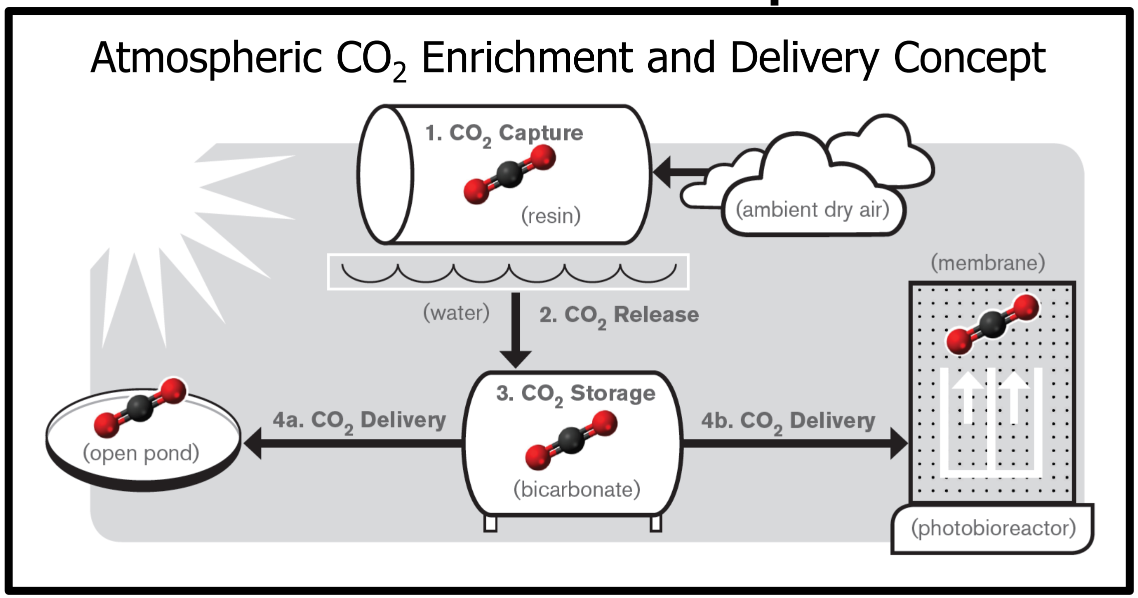
- **History**
  - Bruce Rittmann patented technology using membranes to deliver H_2 to treat wastewater and adapted it for microalgae carbonation in 2011.
  - Klaus Lackner joined ASU in Fall 2014, bringing technology to capture and concentrate CO_2 from ambient air.

- **Objective --**

  Build a system that:

  1. Captures and concentrate atmospheric CO_2
  2. Stores CO_2 in a buffer to ensure adequate supply at any time and further concentrate CO_2 for delivery
  3. Uses bubble-less CO_2 delivery: >90% into media, >70% into biomass

ACED Concept



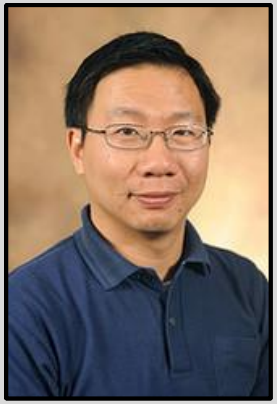
2 – Approach (Management)

Membrane Carbonation (MC)

Key Personnel

Bruce Rittmann

Principal Investigator



Yen-jung Lai

Research Scientist

Everett Eustance

Research Scientist

Justin Flory

Technical Project Manager

Robert Stirling

Techno-Economic Analyst

Moisture Swing Sorption (MSS)

Klaus Lackner

Co-Principal Investigator

Allen Wright

Lead Engineer

Jason Kmon

Engineer

William Barr

Postdoc

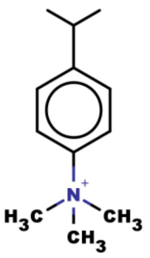
Zara L'Heureux

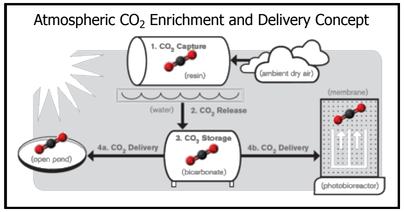
Research Technologist

2 – Approach (Technical)

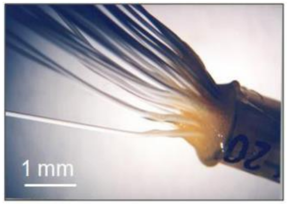
- **Technical Approach**
  - Anionic exchange resin sheets capture CO_2 when dry and release when wet
  - CO_2 is transferred to sodium carbonate/bicarbonate brines to buffer capture and demand rates; thermally extracted and pressurized
  - ~100% CO_2 is delivered on demand to microalgae using membrane fibers
  - System is tested ≥1 months outdoors in a 1500-L pond

Resin





- **Challenges**
  - CO_2 Capture: Support structure cost, resin density, and dead space
  - CO_2 Storage: CO_2 transfer rate and efficiency into and out of brine
  - CO_2 Delivery: Accumulation of non-CO_2 gases in fibers

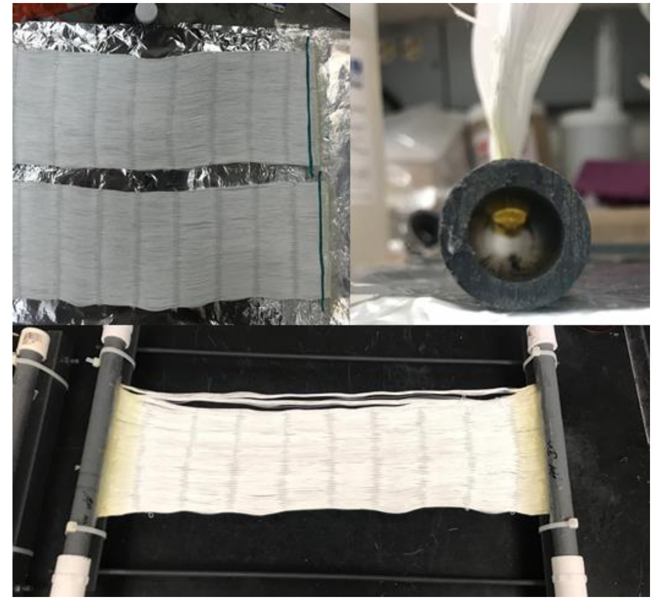


Hollow Fiber Membranes

- **Success Factors**
  - Capture: kg CO_2 / kg resin; kg structure / kg resin
  - Storage: transfer rates; heat recovery; storage cost / kg CO_2
  - Delivery: CO_2 transfer efficiency and flux stability over time

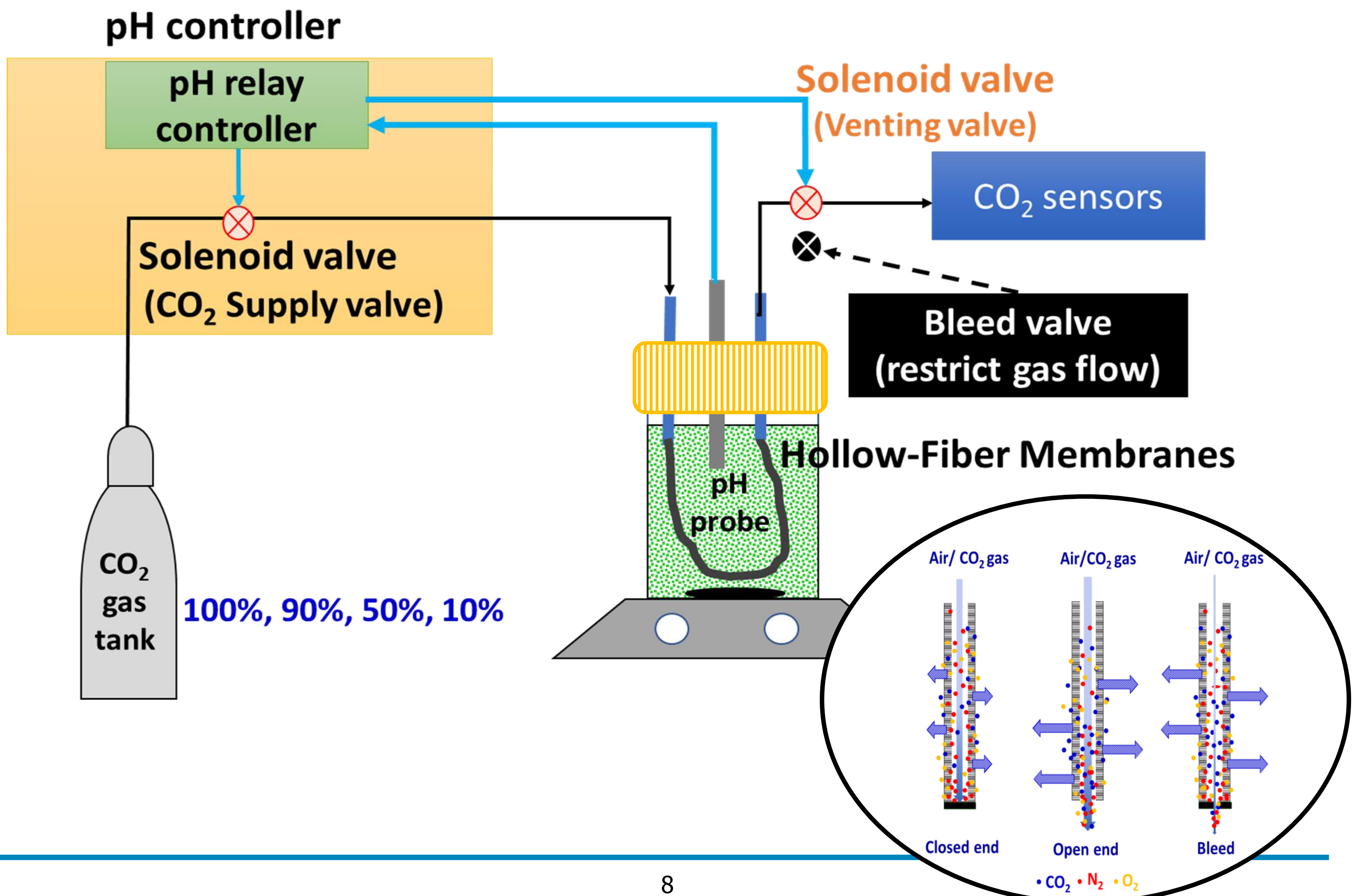
1500-L pond

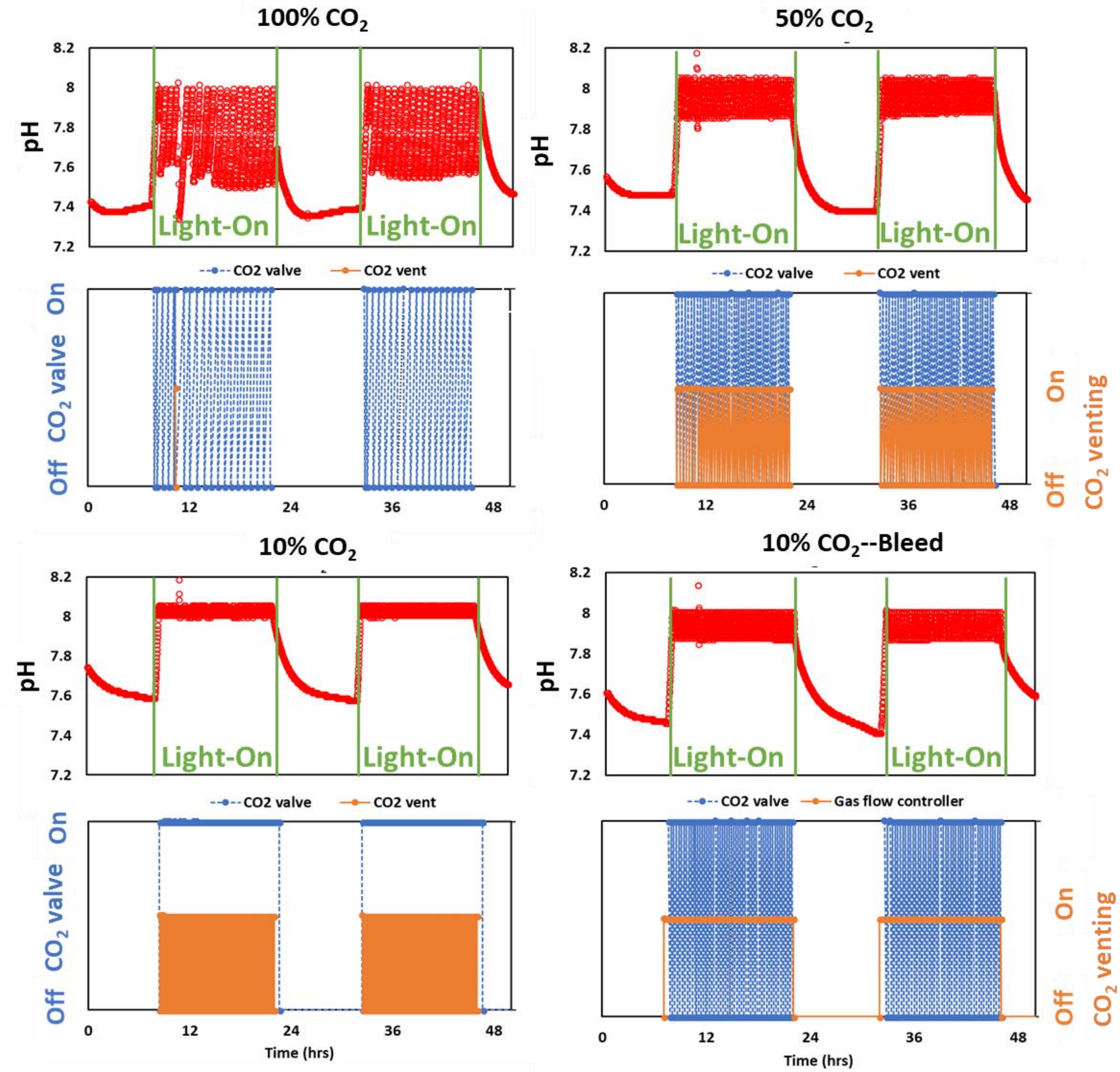
3 – Technical Results (CO_2 Delivery)



1. Biomass productivities were equal and pH control was superior with MC, compared to sparging.
2. ~100% delivery efficiency and 3-fold higher Carbon Utilization Efficiency (CUE) versus sparging.
3. CO_2 delivery rates were not adversely affected by months of operation outdoors.
4. Effective strategies were developed to relieve inert gas accumulation when delivering < 100% CO_2.

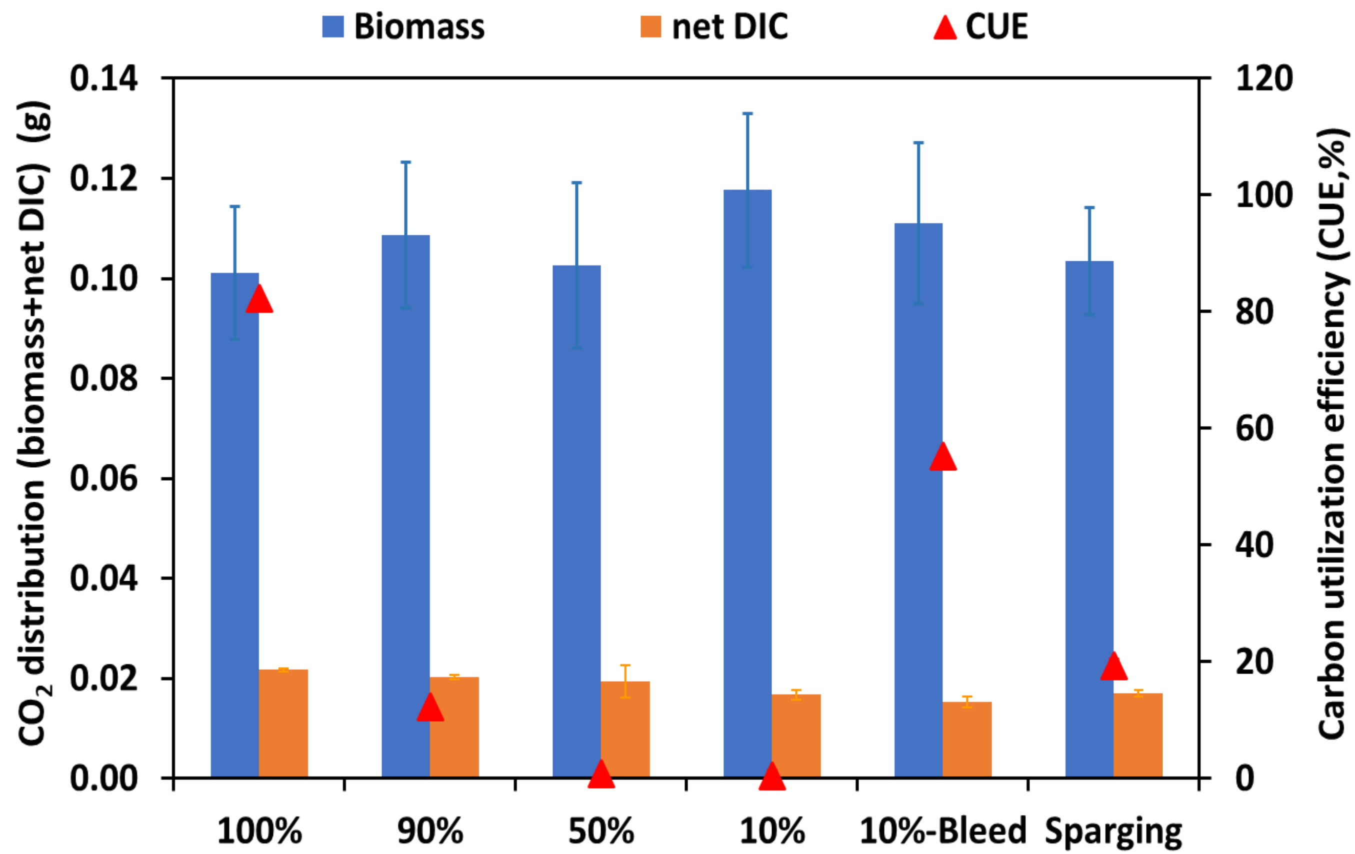
Venting-Bleed MC strategy





100% CO_2
50% CO_2
10% CO_2
10% CO_2--Bleed
pH
8.2
8
7.8
7.6
7.4
7.2
Light-On
CO2 valve
CO2 vent
Gas flow controller
On
Off
CO_2 valve
CO_2 venting
0
12
24
36
48
Time (hrs)

Indoor Carbon-Utilization Efficiency



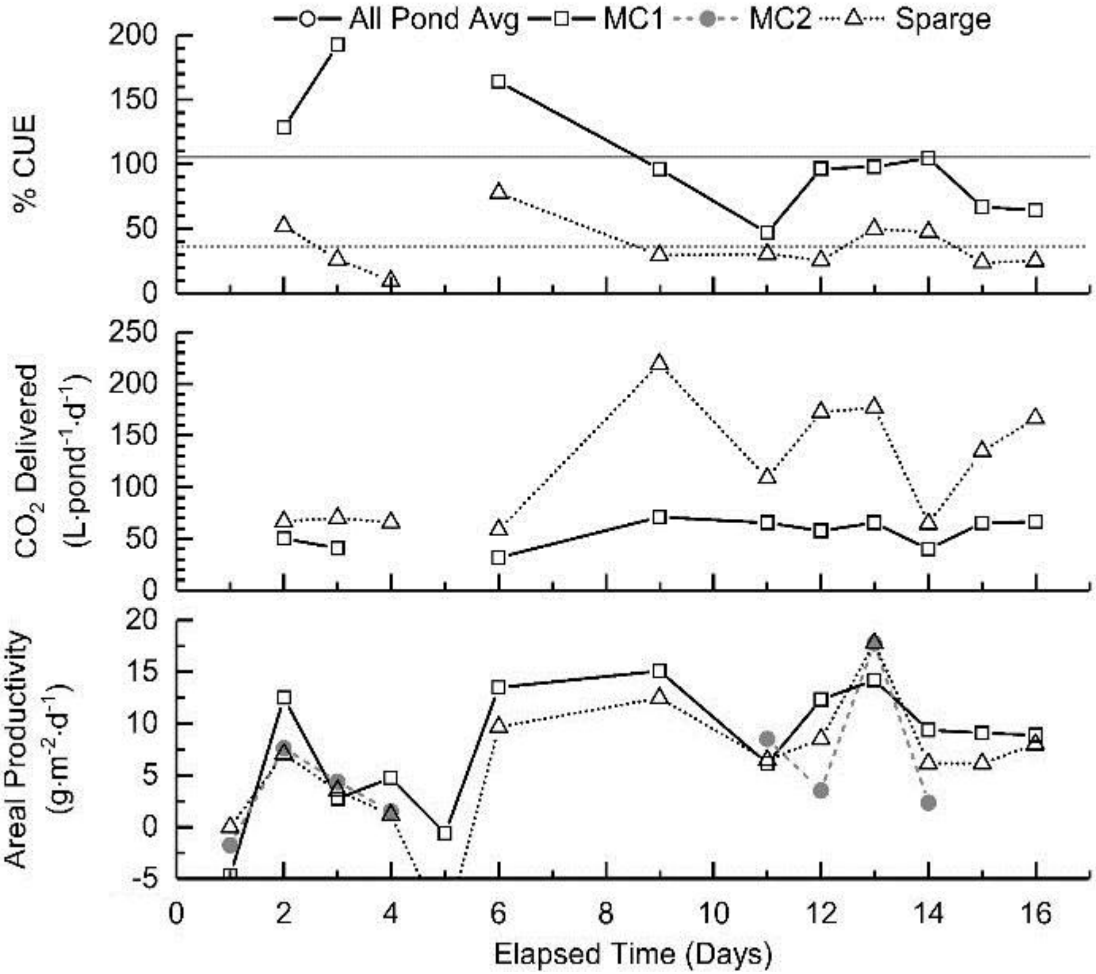
In 100% CO_2: 80% CUE

In 90% CO_2: Low CUE related to small scale of reactors, where we could not cut back the gas flow through the fibers.

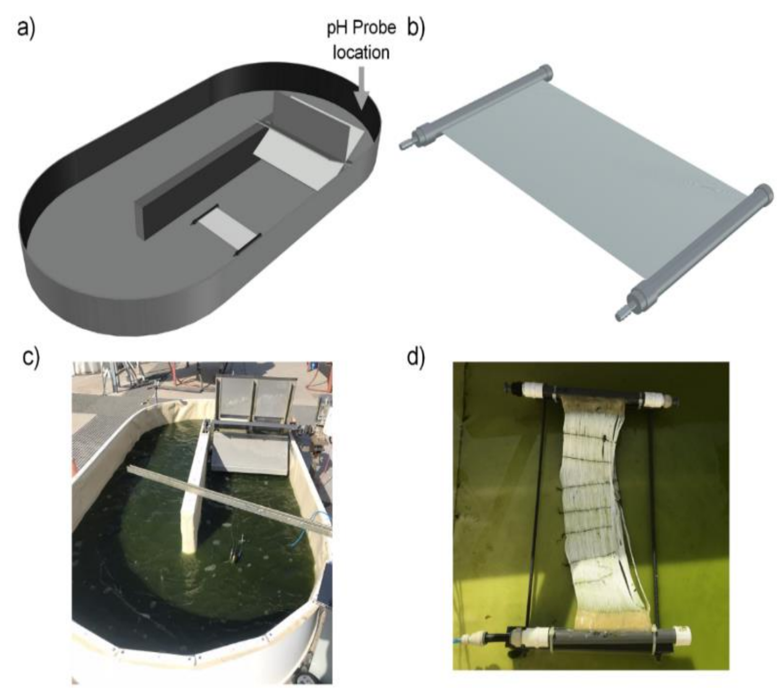
In 10% CO_2 with Bleed: Up to 60% CUE in unoptimized operation (due to small scale)

Outdoor Carbon Capture

- Achieved >100% CUE with pure CO_2 with similar areal productivity as sparging (CUE ~ 40%)
  - 100% delivery + capturing additional CO_2 from atmosphere



Experiment: April 18 to May 4, 2018

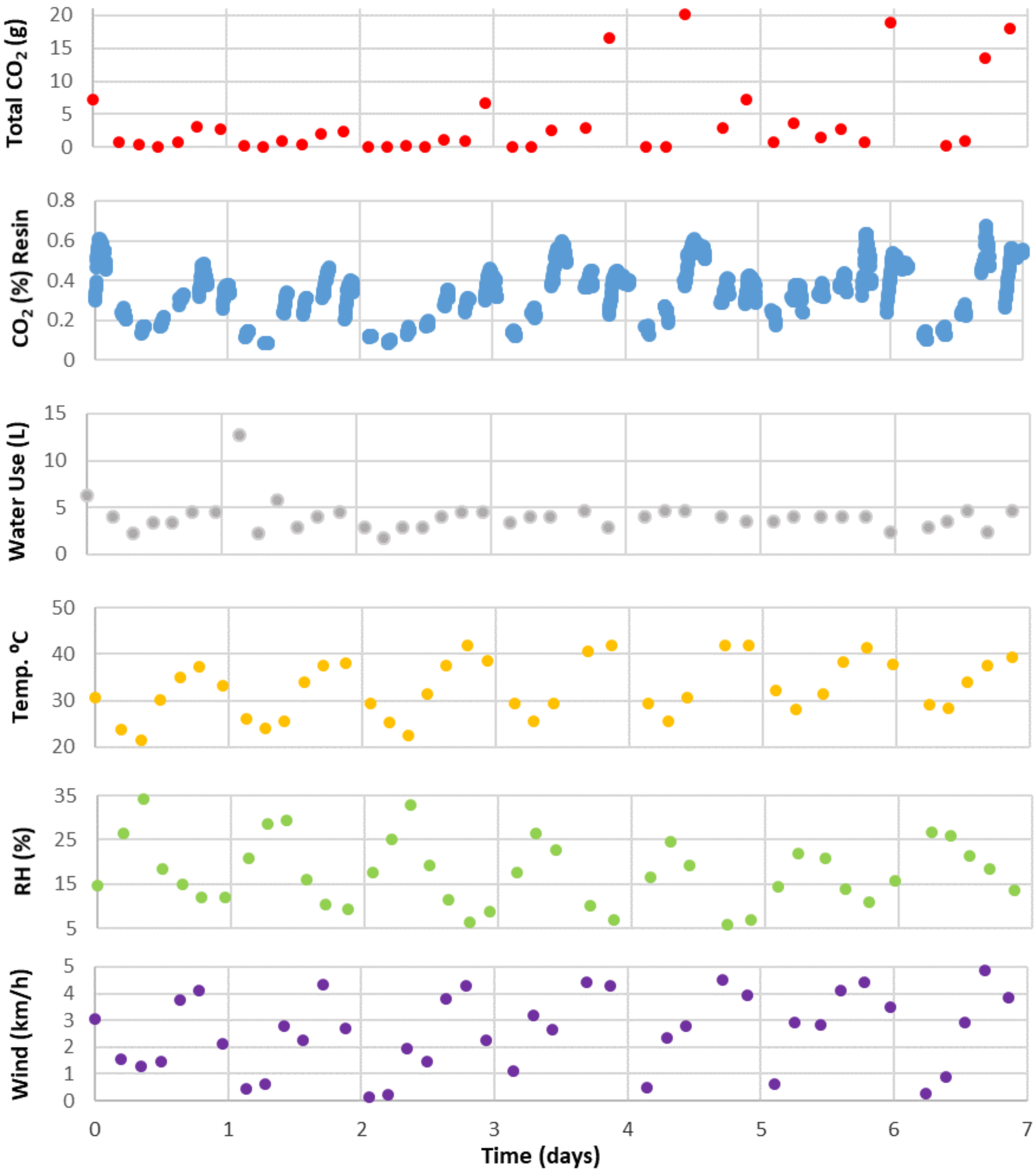


	Experiment 2	Experiment 3	Experiment 4
Dates	3/16 to 4/11/18	4/18 to 5/4/18	5/18 to 6/5/18
pH Setpoint	8.5	8.5	8.0
Average temp (°C)	17.6 ± 4.3	20.3 ± 4.8	23.1 ± 5.1
Average Light ($kWh \cdot m^{-2} \cdot d^{-1}$)	6.2 ± 0.7	7.2 ± 0.8	8.3 ± 0.3
Nitrogen source	Nitrate	Ammonium bicarbonate	Ammonium bicarbonate
Biomass Productivity ($g \cdot m^{-2} \cdot d^{-1}$)	10.2 ± 3.6	6.7 ± 6.0	11.8 ± 6.9
Average fiber flux ($g\text{-}CO_2 \cdot m^{-2} \cdot d^{-1}$)	1360 ± 860	2220 ± 750	2290 ± 610
CUE MC1	67 ± 35%	106 ± 45%	51 ± 27%
CUE Sparging	25 ± 18%	36 ± 19%	17 ± 10%
CUE Ratio MC/Sparging	2.65	2.94	3.0

3 – Technical Results (CO_2 Capture)

1. Over 10% of CO_2 in air was captured by dry resin in lab wind tunnel tests at 1 m/s.
2. A prototype was constructed and captured CO_2 outdoors.
3. Performance data were collected periodically over 6 month and for up to 11 consecutive days; limited by hardware, software, and weather issues.
4. System, and sorbent, survived ~9 months in outdoor conditions, and remained intact.

7 day CO_2 Capture during June, 2018



- Outdoor performance was best when: temperature >25 ºC, wind speed >2 km/h, and < 25% relative humidity.
- Wetting resin to release CO_2 by flooding made resin too wet, slowing drying, reducing performance and wasting water.

3 – Technical Results (CO_2 Capture)

- Adding sodium bicarbonate to supply water mitigated performance reduction from anions in tap water.

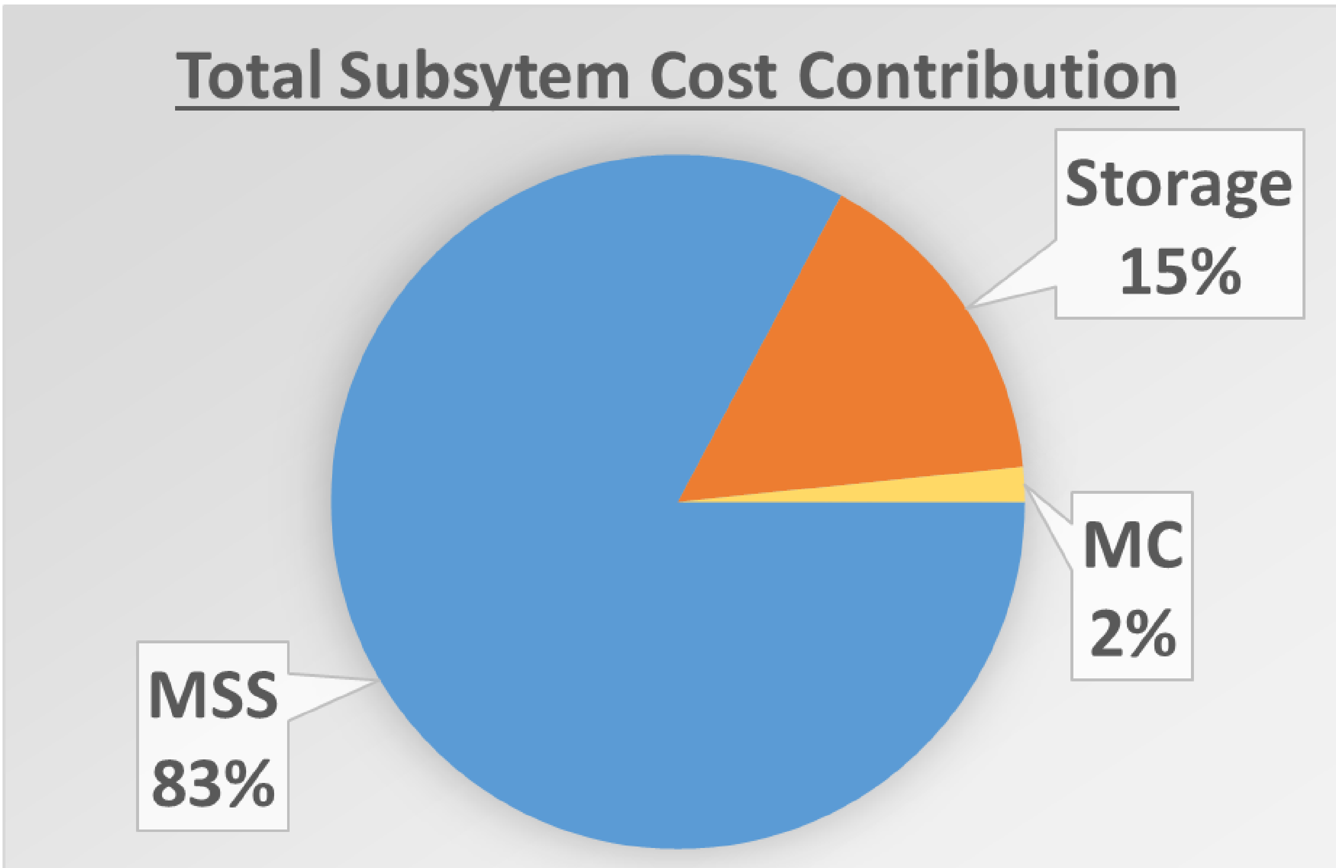
Date	Days in Field (approx.)	Performance (ppm) / % of new	After 1 M Na_2CO_3 wash / % of new	Tapwater [Cl^-]	Tote Water [Cl^-]	Na_2CO_3 in Tote Water?
Feb 2018	60	20 ppm / 11%	100 ppm / 57% (1 x wash)	144 ppm	240 ppm	No
Mar 6, 2018	90				345 ppm	Yes
April 24, 2018	150	55 ppm / 31%	90 ppm / 51% (1 x wash)	259 ppm	369 ppm	Yes
Aug 2-4, 2018	240	60 ppm / 34%	170 ppm / 97% (3 x wash)	173 ppm	637 ppm	Yes
Aug 3, 2018	0 (new)	175 ppm / 100%				

3 – Technical Results (CO_2 Storage)

1. A low-energy system for storage of CO_2 in carbonate/bicarbonate brines was demonstrated.
2. Heating the storage brine to near 100^{o}C releases gas with >90% CO_2 on lab scale and >70% outdoors.
3. A transfer mechanism using wetted fabrics was demonstrated for dissolving captured CO2 into storage brine.
4. The concept to capture CO_2 was demonstrated over a range of concentrations into multiple brine tanks.
5. Software emerged as a major bottleneck in technology development. Software frequently terminated CO_2 delivery into storage prematurely, reducing production.
6. CO_2 flux into storage is highly dependent on the air flow rate and brine composition.

Techno-Economic Analysis

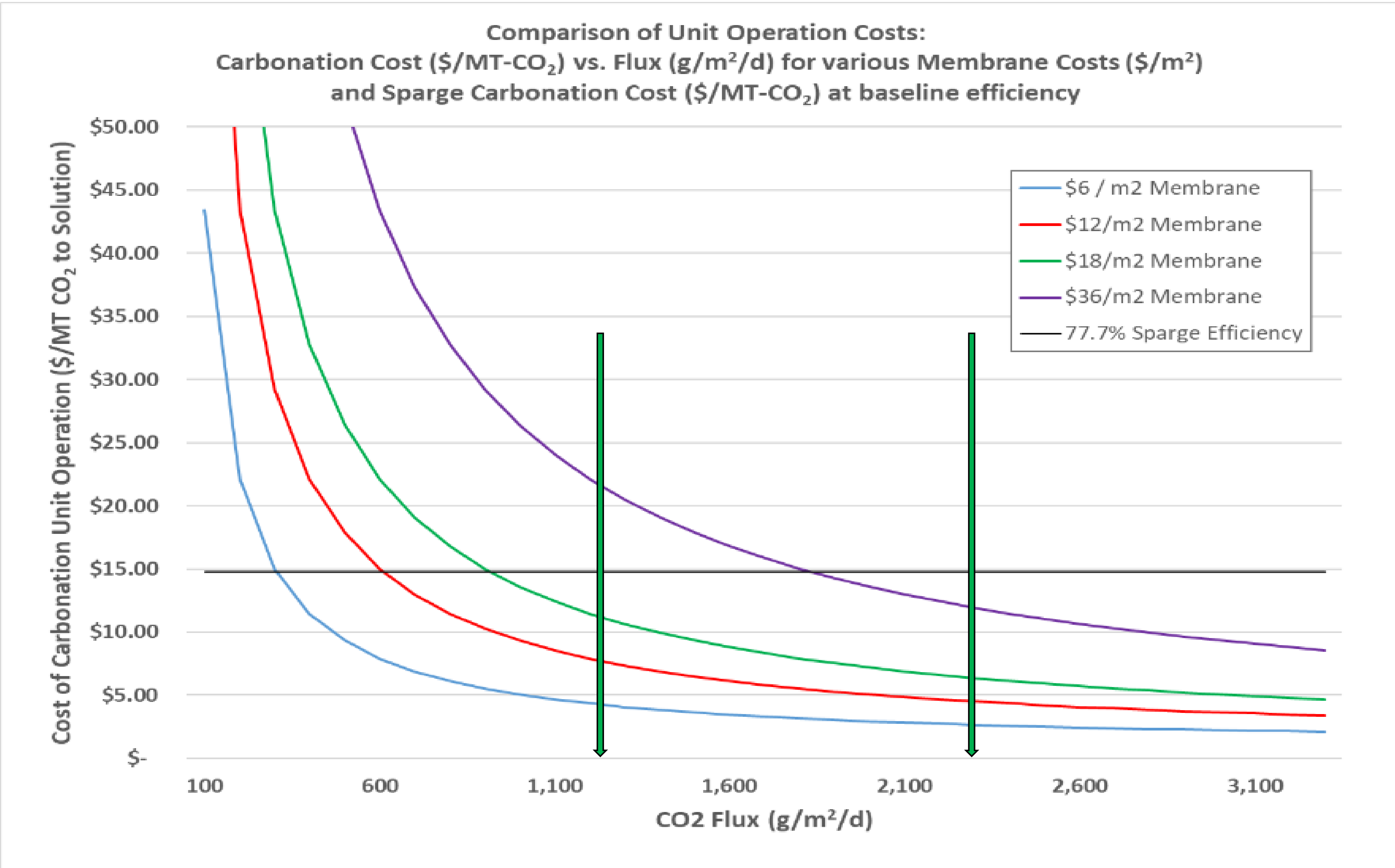
- MC contributed a small amount in comparison with prototype CO_2 capture and storage device



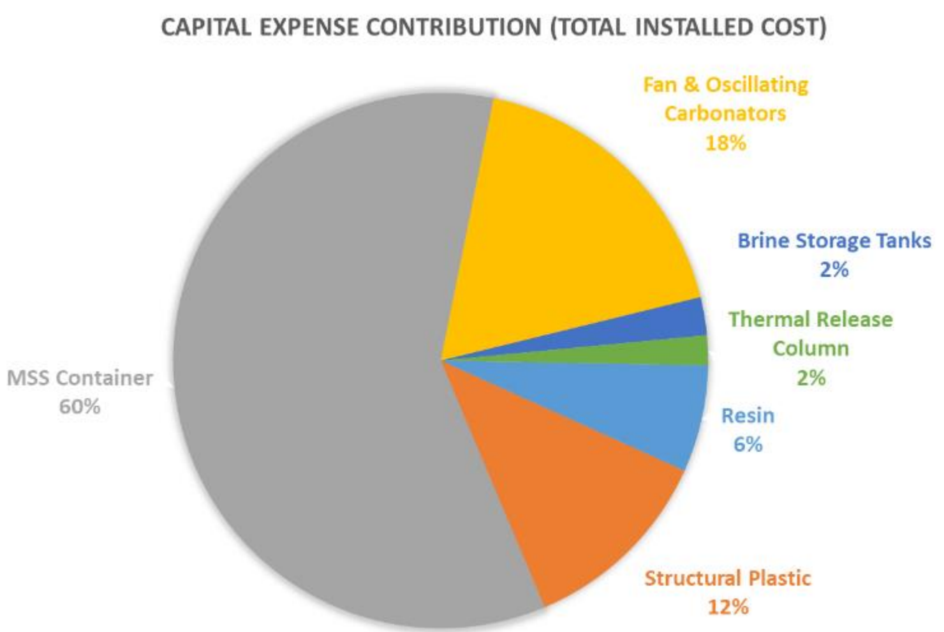
Techno-Economic Analysis - MC

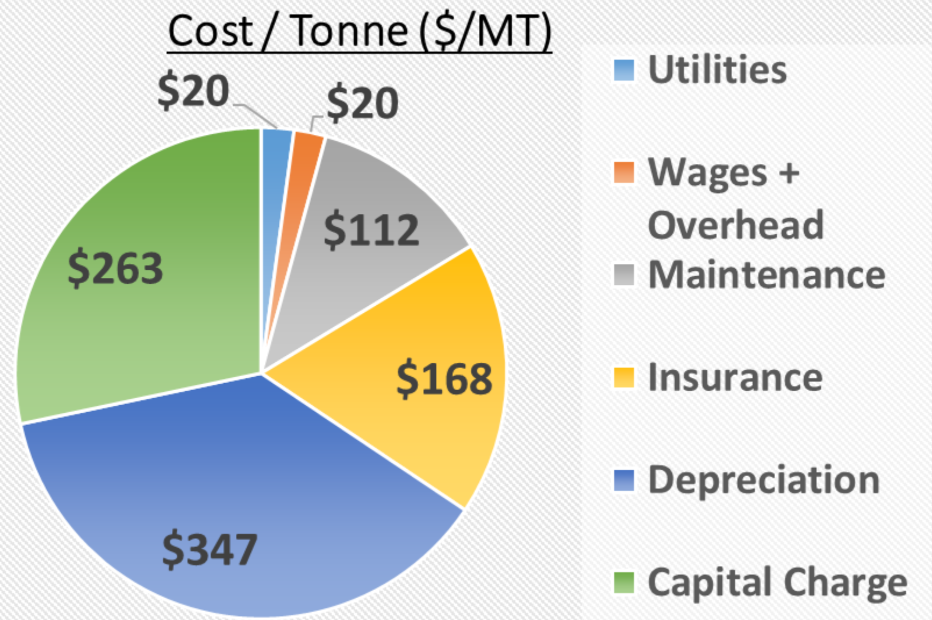
- MC reduces the cost of supplying CO_2 by at least 40–50% for current operators who pay $120–500 / tonne for CO_2.
- MC should reduce total CO_2 costs by 15–20% at the large scales envisioned by BETO.
- Cost of operating MC is less than sump sparging at 80% efficiency. MC fluxes greater than 1800 g-CO_2/m^2-d has an install cost of ~ $3/MT CO_2 delivered.

Install Cost for MC VS Sparging



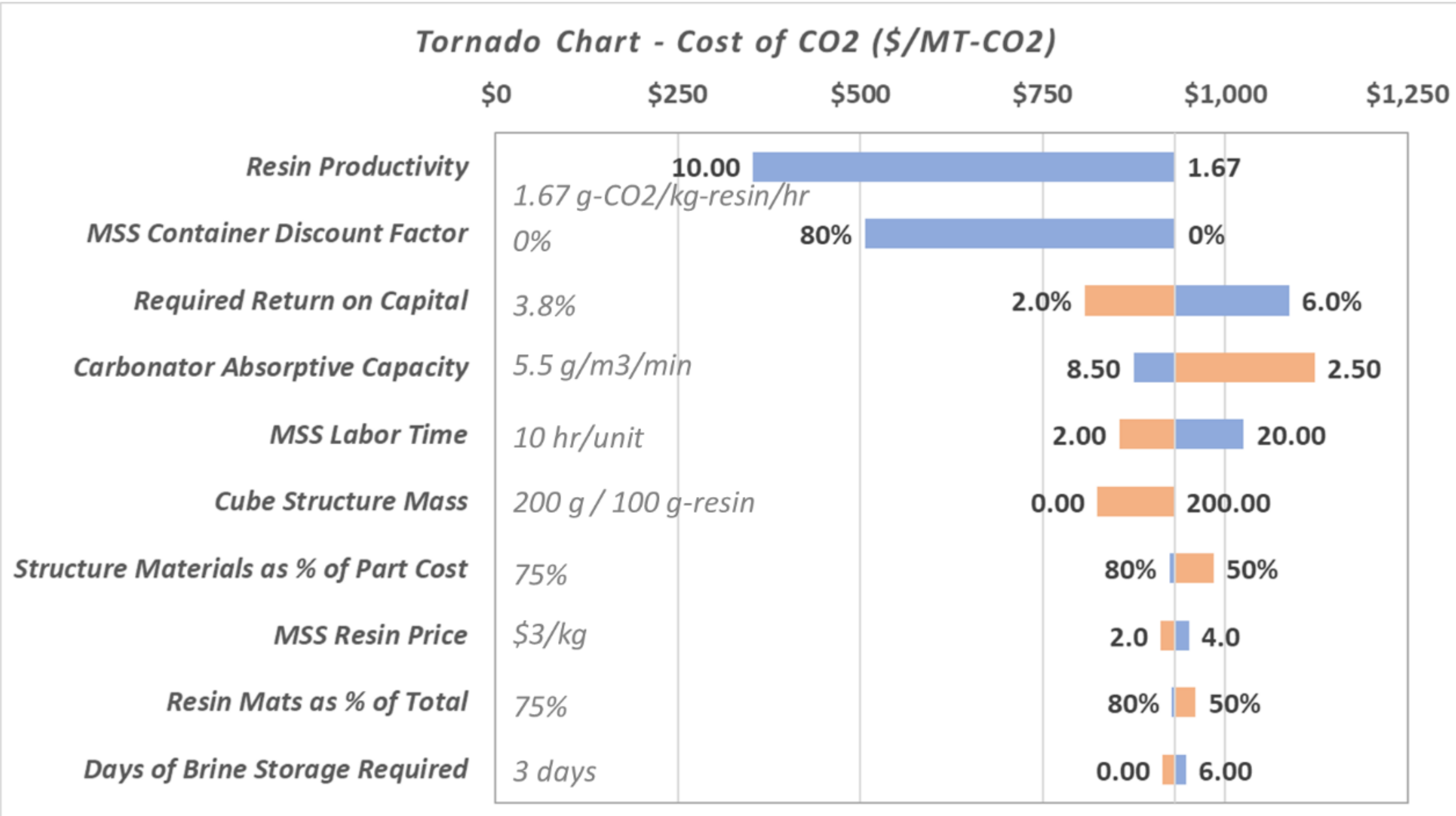
Techno-Economic Analysis MSS





- Extrapolating the Prototype housing design to large scale leads to an estimated cost of dissolved, bioavailable CO_2 of ~**$900 per metric ton**.
- The majority of the cost comes from the CapEx required to enclose, wet, and dry the functional resin.

TEA: Tornado Chart for MSS



Observations & Recommendations:

1. Maximize resin productivity
2. Minimize MSS container cost

Blue = Assumption Increases
Orange = Assumption Decreases

Relevance

- **Goal:** Design, build, and demonstrate outdoors a system for capturing and concentrating CO_2 from ambient air and delivering the CO_2 to microalgae.
  - Each component worked on its own.
  - Integration was not achieved due to hardware and software failures in MSS.
- **Demonstrated ≥100% CO_2 delivery using MC outside**
- **Industry Relevance**
  - We definitely can deliver concentrated CO_2 into PBR with ~100% efficiency
  - This provides a major cost saving for delivering concentrated CO_2
- **Project Impact**
  - Efficient CO_2 delivery enables high productivities
- **Marketability**
  - **MC**: Besides pairing with MSS, MC can work with flue gas, digester gas, fermenter off-gas, landfill gas, and more.

Summary

- **Overview**
  - Provide concentrated CO_2 in sunny locales far from concentrated sources and delivered into PBRs with ~100% efficiency.
- **Approach**
  - Moisture swing sorption CO_2 capture + carbonate brine storage + membrane carbonation for CO_2 delivery.
- **Technical Accomplishments / Results**
  - All subsystems were validated: CO_2 was captured, stored in brine, extracted from brine, an delivered to microalgae.
  - We achieved outdoor demonstration of the MC part of ACED.
  - MSS components worked, but could not be integrated due to failures.
- **Relevance**
  - Efficient CO_2 delivery <u>enables</u> high productivities
  - In addition to MSS, MC can work with flue gas, digester gas, fermenter off-gas, landfill gas, and more.

Questions?

Bruce Rittmann, Ph.D.
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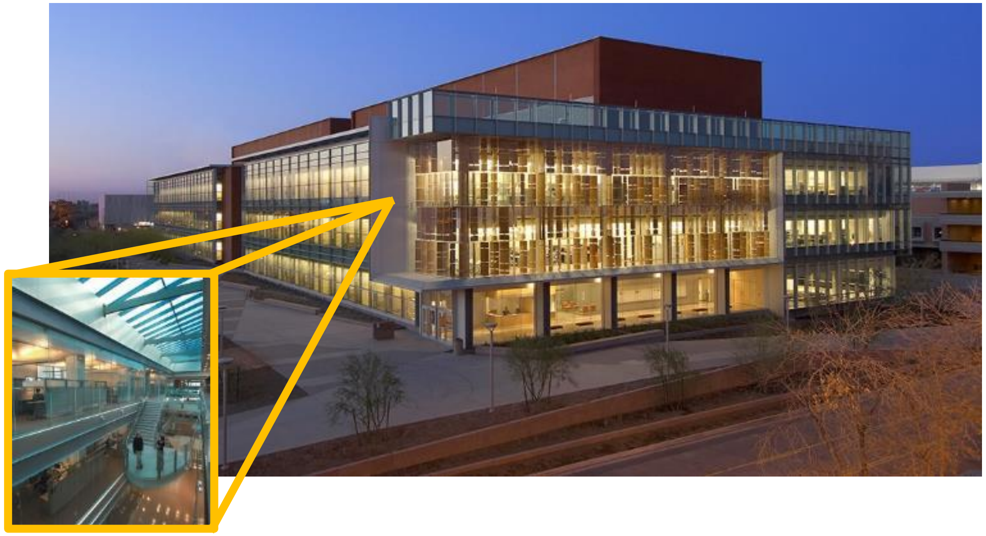
Director, Swette Center for Environmental Biotechnology
Regents' Professor of Environmental Engineering
The Biodesign Institute
Arizona State University

Arizona State University

Biodesign Institute



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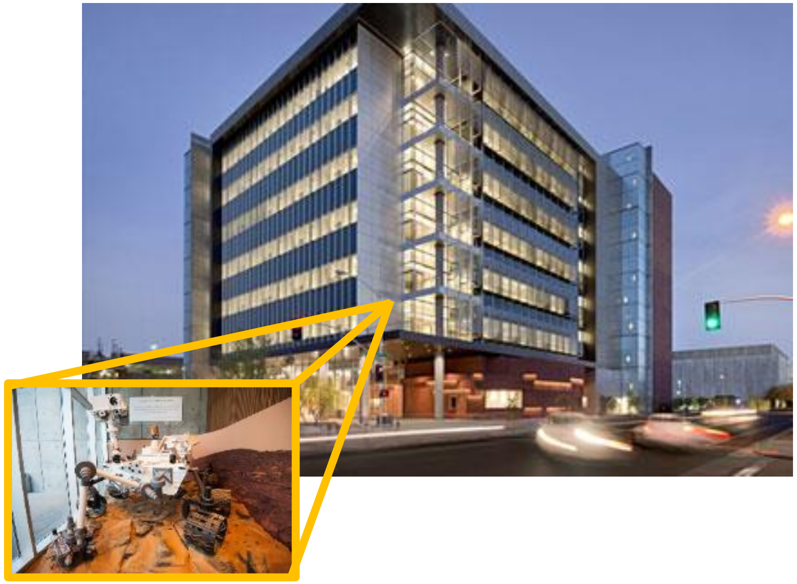

Arizona Center for Algae Technology and Innovation (AzCATI)

Supporting Slides

Publications, Patents, Presentations, Awards, and Commercialization

- **Publications**
  - Characterization of CO_2 Flux Through Hollow-Fiber Membranes Using pH Modeling (Submitted-2018). Journal of Membrane Science. Tarun Shesh, Everett Eustance, Yen-Jung Lai, Bruce Rittmann
  - Shi, X., Xiao, H., Liao, X., Armstrong, M., Chen, X. and Lackner, K.S., 2018. Humidity effect on ion behaviors of moisture-driven CO2 sorbents. The Journal of Chemical Physics, 149(16), p.164708.
- **Awards:**
  - DOE grant DE-EE0008517: "Membrane Carbonation for 100% Efficient Delivery of CO_2 from Industrial Gases"
  - DOE grant DE-FOA-0001858: "Mining Air for Fuels and Fine Chemicals"
  - Bruce Rittmann, 2018 Stockholm Water Prize
- **Patents:**
  - Use of Hydrophobic Coatings on Direct Air Capture Sorbents Used for Carbon Dioxide Removal from Air. 62/752,725. Wright and Lackner
  - Microalgae-driven CO_2 removal from mixed gases using hollow fiber membranes. Internal ASU disclosure M19-138L. Everett Eustance, Bruce Rittmann, Yen-Jung Lai, Tarun Shesh, Justin Flory
- **Commercialization: Nothing to report yet**

Publications, Patents, Presentations, Awards, and Commercialization

- **Presentations**
  - Klaus Lackner, *CO_2 Removal Steering Group Meeting, La Jolla, CA.* Feb. 22-23, 2018
  - Klaus Lackner, "Research and development for CO_2 Removal" *The 4th Science & Energy workshop, École de Physique des Houches, Les Houches, France.* Mar. 4-9, 2018
  - Klaus Lackner, "Cleaning up Climate Change; A Business Opportunity" *American Gas Association's Sustainable Growth Committee, Scottsdale, AZ.* Mar. 15, 2018
  - Klaus Lackner, "45Q-The new carbon economy" *Earth Day (EarthX 2018), Dallas, TX.* April 21, 2018
  - Klaus Lackner, "Direct Air Capture" *REVERSAPALOOZA- A summit to jumpstart a new carbon removal marketplace, Seattle, WA.* April 26, 2018
  - Klaus Lackner, "The New carbon economy" *AREDAY Summit, American Renewable Energy Day, Aspen, CO.* June 21, 2018
  - Klaus Lackner, "Recovering from the overshoot in Carbon Dioxide Emissions" The University of Edinburgh, Germany. July 5, 2018
  - Klaus Lackner, "CCS and Direct Air Capture" Circular Carbon Economy, Golden CO. July 24, 2018
  - Klaus Lackner, "Strategies for lowering the cost of direct air capture" Google X, Menlo Park CA. August 21, 2018
  - Klaus Lackner, "Cleaning up our carbon dioxide waste: Technologies to achieve global climate targets" Elizabeth and Frederick White Conference on Gas–Solid Reactions, Australia. September 6, 2018
  - Klaus Lackner, "Introduction to Center for Negative Emissions at ASU" Negative Emissions Technologies in the Energy Sector Workshop, Houston TX. September 14, 2018

Publications, Patents, Presentations, Awards, and Commercialization

- **Presentations (cont)**
  - Klaus Lackner, “Reflections on IPCC Perspectives and CO2 Capture from the Air” 2018 CCUS STUDENT WEEK, Golden CO. October 15, 2018
  - Everett Eustance, “Membrane Carbonation for Improved Carbon Capture Efficiency in Algal Cultivation”, Algae Biomass Summit. The Woodlands, TX. October 15, 2018

Responses to Previous Reviewers' Comments

- This project is attempting two innovative developments. One is for capturing atmospheric CO_2 using a "filter unit," and the other is a new method for delivering CO_2 to PBRs using membranes. I would rather these were separate projects so the focus would be strengthened. The approach for releasing CO_2 from a carbonate mixture and delivering gaseous CO_2 to the media using membranes has several processing steps, equipment, and requires energy input. It is not clear to me the cost-benefit of this approach, as we could much more directly feed the carbonate solution to the media. The cost of the filter unit is prohibitive. I understand that the project is exploring cost-reduction ideas for the filter unit. If the team is not able to significantly reduce the cost of the filter unit, maybe they will be able to recommend where additional research is needed to potentially make this approach feasible in the future.

- In principal, the carbonate/bicarbonate storage solution could be fed directly to the PBR in lieu of extracting and compressing the CO_2 gas for delivery via MC. However, this approach presents several problems: (1) photosynthesis normally drives up the pH by consuming inorganic carbon and reducing nitrate, so delivering the acidic form avoids the need for adding acid to regulate the pH; (2) delivering bicarbonate requires a balancing cation, usually Na+, which increases the salt concentration; and (3) the storage tank contains a mixture of carbonate and bicarbonate at high pH such that it can more efficiently take up CO_2 delivered from the capture system, whereas PBRs are typically operated at a pH near 8.5. Thus, adding bicarbonate from storage will tend to increase the pH of the bioreactor, requiring compensating forms of acidity. Put another way, extracting accumulating alkalinity from the algae pond would be expensive. The storage system, as designed, retains the alkalinity in the storage tank and only transfers CO_2 to the microalgae.

- Another more direct approach might be to deliver captured CO_2 directly to the PBR using a fabric contactor and bypassing the storage subsystem. As part of the final report, the team will suggest future lines of research to address commercial feasibility.

- These are responses to the 2017 peer review.