Development of high value bioproducts and enhancement of direct-air capture efficiency with a marine algae biofuel production system

Zackary Johnson

April 2023

Algae Platform Review

DOE Bioenergy Technologies Office (BETO)
2023 Project Peer Review

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

B&D

MoleculeWorks
Efficiency for a Sustainable World

WBS 1.3.4.010

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Project Overview

This team was spun out of the MAGIC-C (WBS 1.3.2.440) consortium, and represents a similar group with one new member (MW) who brings specialized DAC experience

Our focus here is to build on substantial team experience associated with outdoor algae cultivation, CO_2 conversion, and TEA/LCA of algae biofuels to develop and test approaches to generate CO_2 from DAC for algae use, while simultaneously improving economics through cultivation improvements and co-product development

Success means improved algae biofuel economics and reduced environmental impact

FOA: DE-FOA-0002203 Algae Bioproducts and CO2 Direct-Air-Capture Efficiency (ABCDE)

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1- Approach

Project Goal

To demonstrate high-performance algae cultivation using carbon sourced from DAC coupled with stable DIC production to generate fuel and high-value co-products at a commercially relevant scale, and then to deliver techno-economic and life-cycle assessments that illustrate the associated economic and environmental benefits at commercial scale.

Our 3 specific goals are:

– *increase the revenue of the algae biomass while ensuring that fuel specifications are met*

– *Increase productivity over baseline levels while using carbon supplied by DAC*

– *increase the percentage of carbon supplied by DAC while still reducing the costs associated with supplying CO_2*

FOA Goals: Projects will, by the end of the research, deliver techno-economic analyses utilizing data generated from the R&D that show lower potential algal biomass costs and increased potential revenue from the incorporation of DAC with production of valuable algae products

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2 – Approach (Technical)

Components (by Task Number)

2) ***Strain Assessment and Cultivation*** will (1) demonstrate biochemical characteristics of marine microalgae that have demonstrated value that exceed current algae biomass uses (focusing on collagen and whey replacements) and to (2) demonstrate design and operational characteristics of microalgae cultivation that enhance productivity compared to base cases (Duke)
3) ***DAC CO_2 and Conversion*** will demonstrate cost effective direct air capture of CO_2 and subsequent conversion to HCO_3 towards broader increased efficiency of algae growth (reduced CO_2 losses and increased growth/yield) (MW/UCSC)
4) ***Demonstration*** will translate laboratory results in (1) production of strains with high value co-products outside (2) algae growth/yield on DAC and converted CO_2 (i.e. coupled system) (3) operational changes outside to enhance productivity (Duke)
5) ***TEA/LCA*** will ground experimental data from various scales into a larger commercialization and biofuel development effort towards identifying the processes and factors that affect costs and environmental impacts (B&D)

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1 - Approach (Major Tasks)

- Task 1: Verification
- **Task 2: Strain assessment** (Cultivation) – Co-product screening, data/modeling for pond operation/capital redesign → **co-products; ↑ economics from lower cost/higher value**
  - Risk / management: no co-product, no desirable response / multiple strains & down selection
- **Task 3: DAC CO_2 & conversion** CO_2 to HCO_3 using $CaCO_3$→ **uncoupled from pipe/ reduced CO_2 use**
  - Risk / management: poor performance / design & iterate
- **Task 4: Demonstration** - integrated system, industrially relevant scale→ **translation to industry**
  - Risk / management: scale-up does not translate / multiple scales & strains
- **Task 5: TEA/LCA & System Modeling**→ **economics/sustainability**
  - Risk / management: limited risk

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Relevance and Impact

Topic Area 3 Metrics	How addressed in this project
Algal biomass revenue potential	• EPA/DHA co-production – \$400,000/tonne • Collagen peptide co-production – \$40,000/tonne • Whey protein replacement co-production – \$1,800/tonne
Algal biomass quality	• Biochemical characterization for all co-products
Algae areal productivity	• Modification of cultivation procedures: “stocking density” • Modification of cultivation infrastructure design: ↑O_2 degassing; ↓ CAPEX / OPEX
DAC CO_2 delivered and utilized by algal system	• Novel membrane based DAC of CO_2 and conversion to DIC • Modification of cultivation infrastructure design: ↑ CO_2 flux
Cost of CO_2	• Novel membrane based DAC and DIC = \$52/tonne CO_2

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2 - Progress and Outcomes

Task 2: Strain assessment: *ID of strains with high value co-products*

StrainID	Species	Origin	Outdoor	$\geq 18 g/m^2/d$	EPA	Collagen	Whey
Ocy3	*Oocystis sp.*	MAGIC	×				
S002	*Oocystis sp.*	MAGIC	×				
Pico	*Picochlorum cereli*	SOT (Exxon)		×			
C985	*Tetraselmis sp.*	MAGIC	×		×		
C018	*Nannochloropsis sp.*	MAGIC	×	×	×		
H1117	*Chlorella sp.*	MAGIC	×		×		
D046	*Desmodesmus sp.*	MAGIC	×				
C046	*Desmodesmus sp.*	MAGIC	×	×			
UTEX646	*Phaeodactylum tricornutum*	SOT (UTEX)					
C417	*Nannochloropsis oceanica*	MAGIC / USDA	×	×	×		
NREL39-A8	*Picochlorum renovo*	SOT					
DOE1116	*Porphyridium cruentum*	SOT		×			
CCMP819	*Stichococcus minor*	SOT (CCMP)		×			
CCMP2329	*Picochlorum oklahomenisis*	SOT (CCMP)		×			
DOE0152.z	*Scenedesmus rubescens*	SOT (CCMP)		×			

Screening protocols developed and ongoing → ~2/3 done

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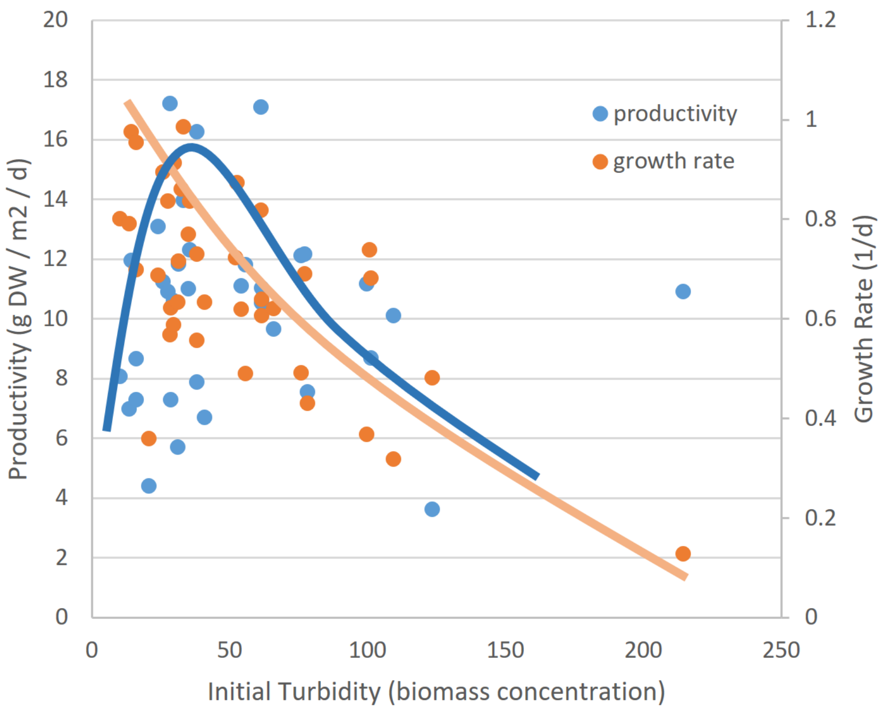
Task 2 (part 2): Stocking Density Influences Performance



Relationship between growth rate, productivity and stocking density (turbidity)

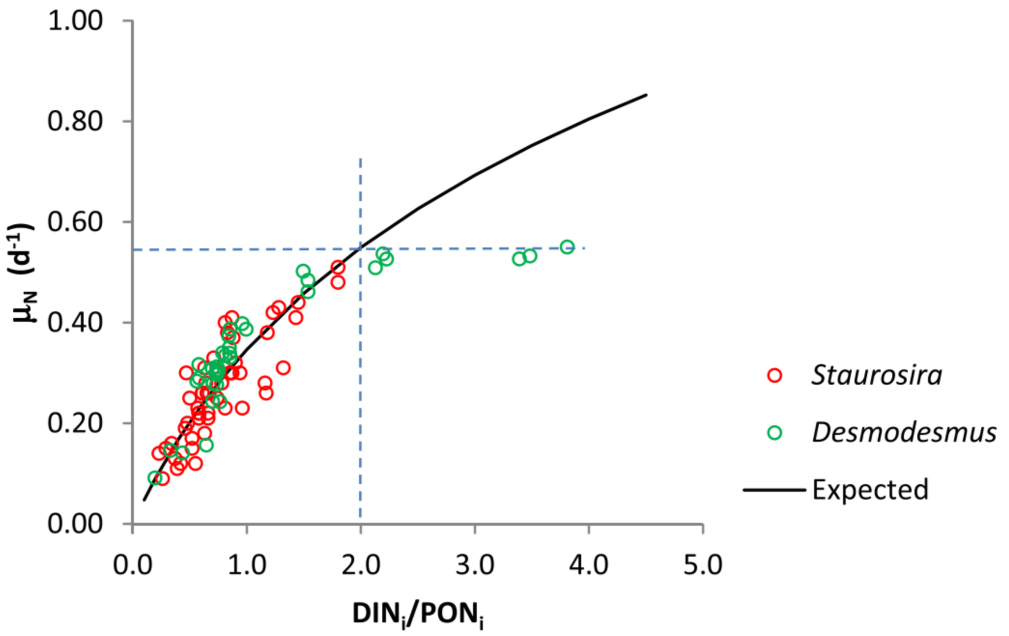


Fig. 5. Doubling rate of PON, μ_N (d^{-1}), as a function of the fertilizer ratio, DIN$_i$/PON$_i$, on D 2 for *Staurosira* (○) and *Desmodesmus* (○), compared to the expected doubling rate if DIN is converted to PON, based on Eq. (3). The dashed lines indicate values used for t Base Case.

Empirically derived results for a few strains – need a mechanistic understanding to generalize

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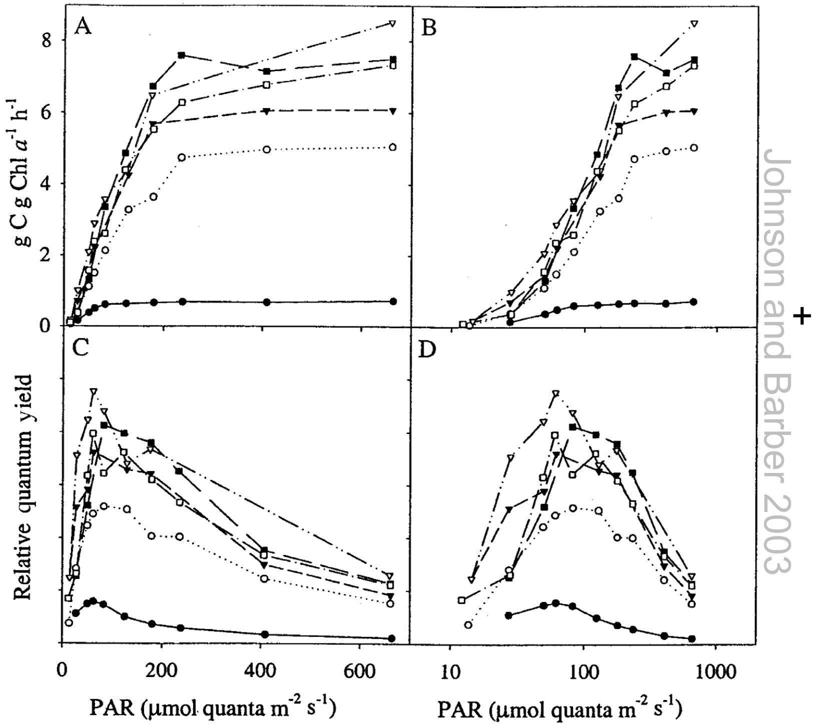
Mechanistically Optimizing "Stocking Density"

- Mechanistic Model: Photosynthesis-Irradiance curves + Light = Predicted Productivity



-E on a (A) linear and (B) common log abscissa scale and associated relative ϕ_C-E on a (C) linear and (D) common log
tylum brightwellii (closed circles), *Dunaliella euchlora* (open circles), *Thalassiosira fluviatilis* (closed triangles), *Isochrysis*

Johnson and Barber 2003

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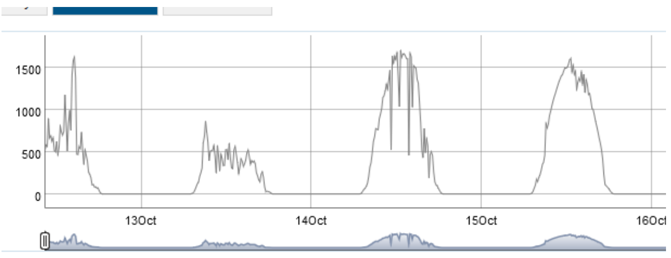

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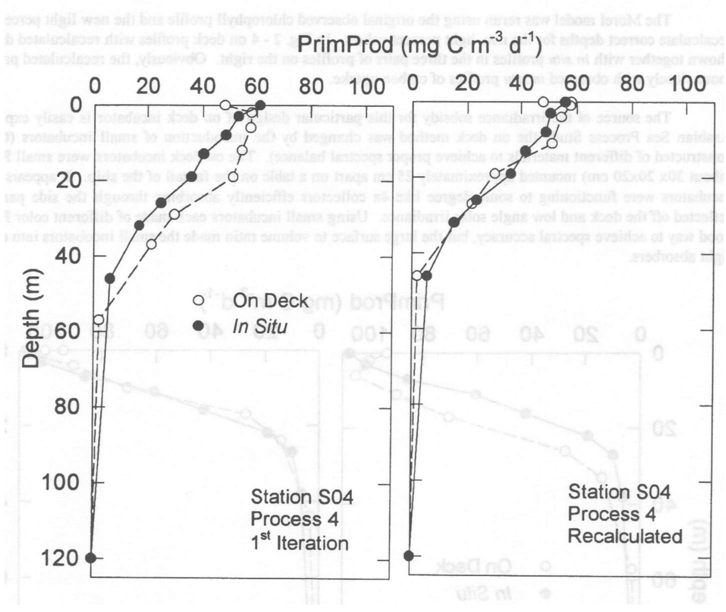

Barber et al 1997

- Test identified condition(s) at lab scale

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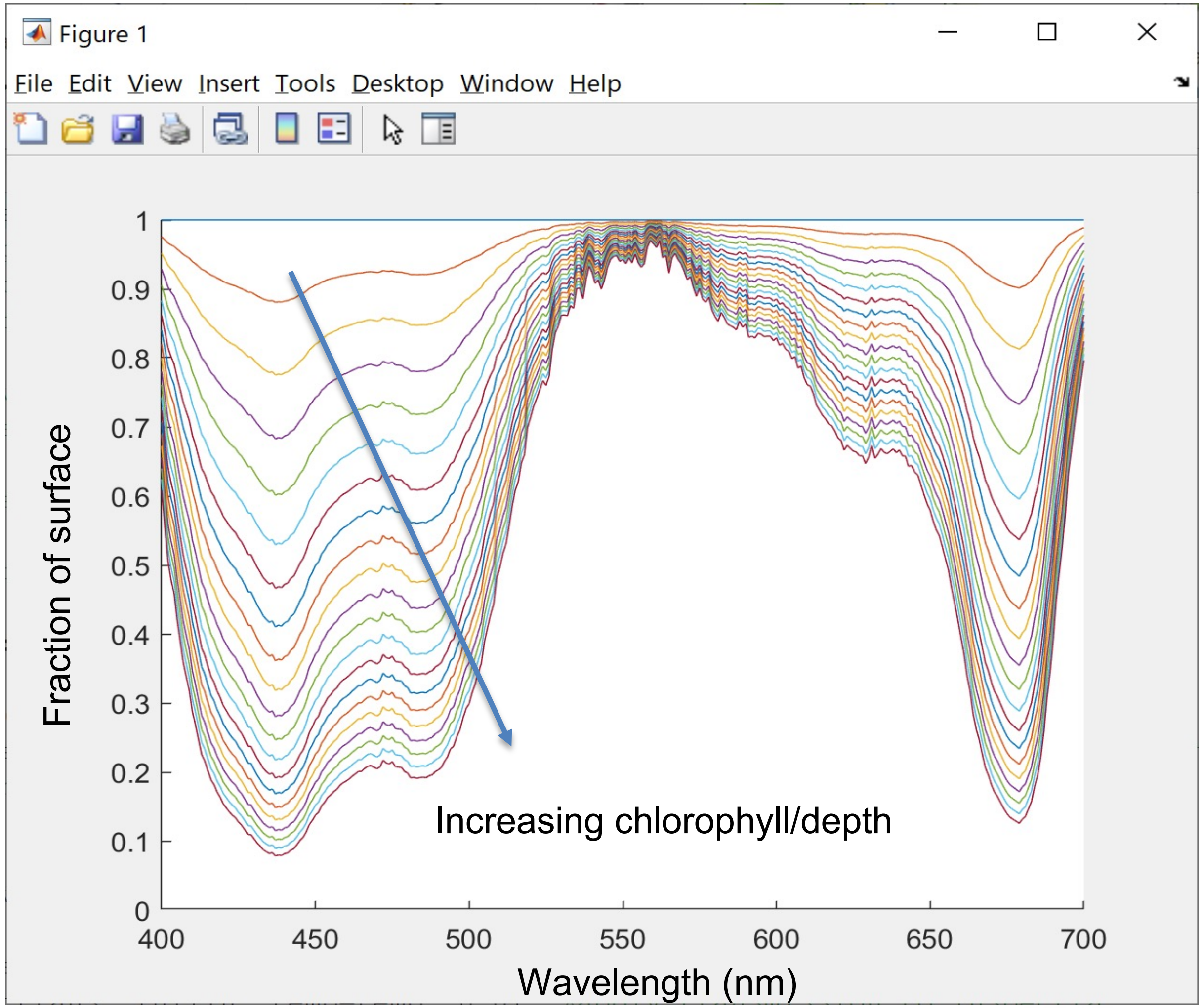
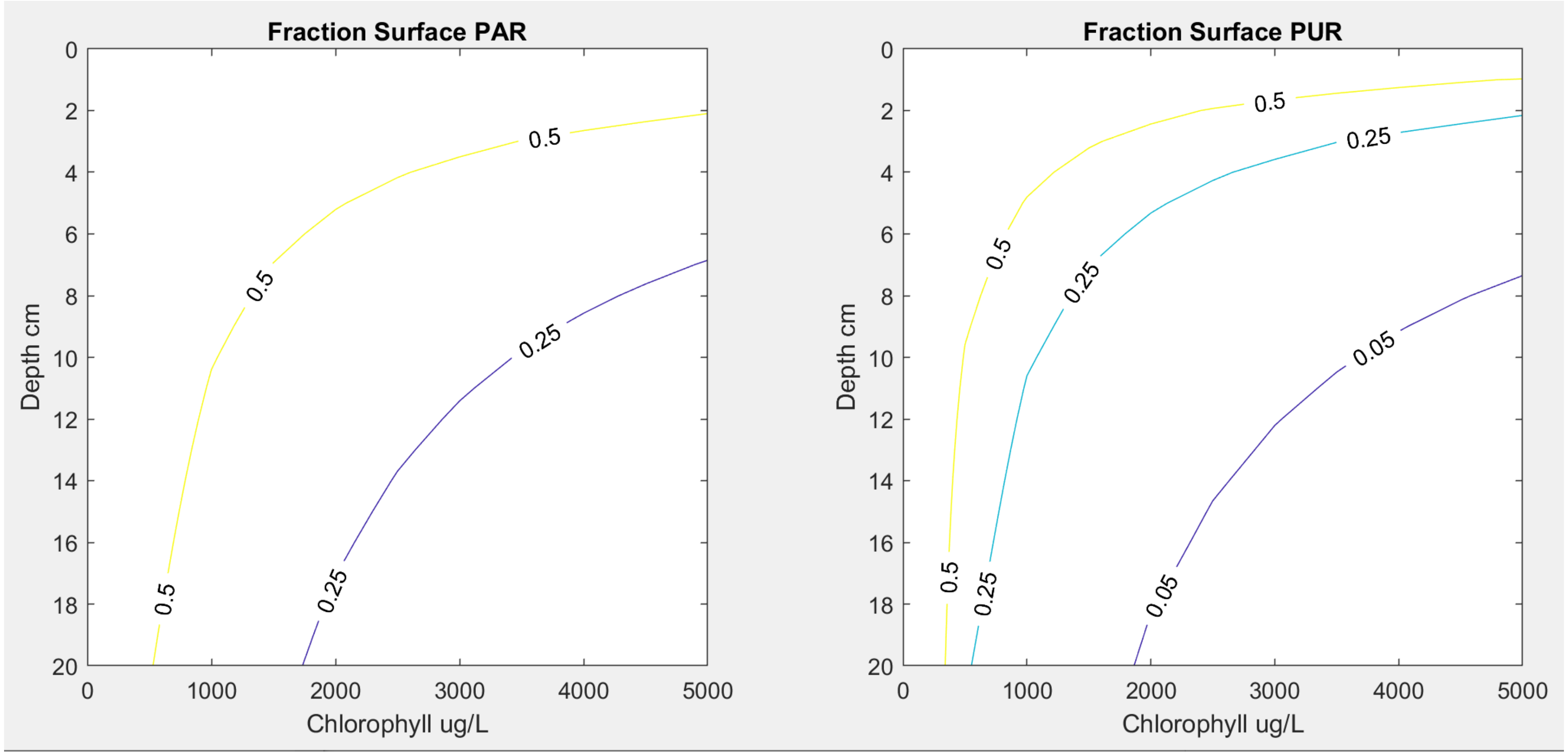
Steps towards mechanistic production model

- Measure high resolution spectral absorption (see supplemental)
- Propagate light field using custom model (in MATLAB, right)
- (Next slide) report relative to surface for:
  range of chlorophyll (biomass)
  range of depths (cm)



Model output: light field for any depth at any stocking density



H1117 (*Chlorella*) grown at 800 µmol Q m^2 sec^{-1}

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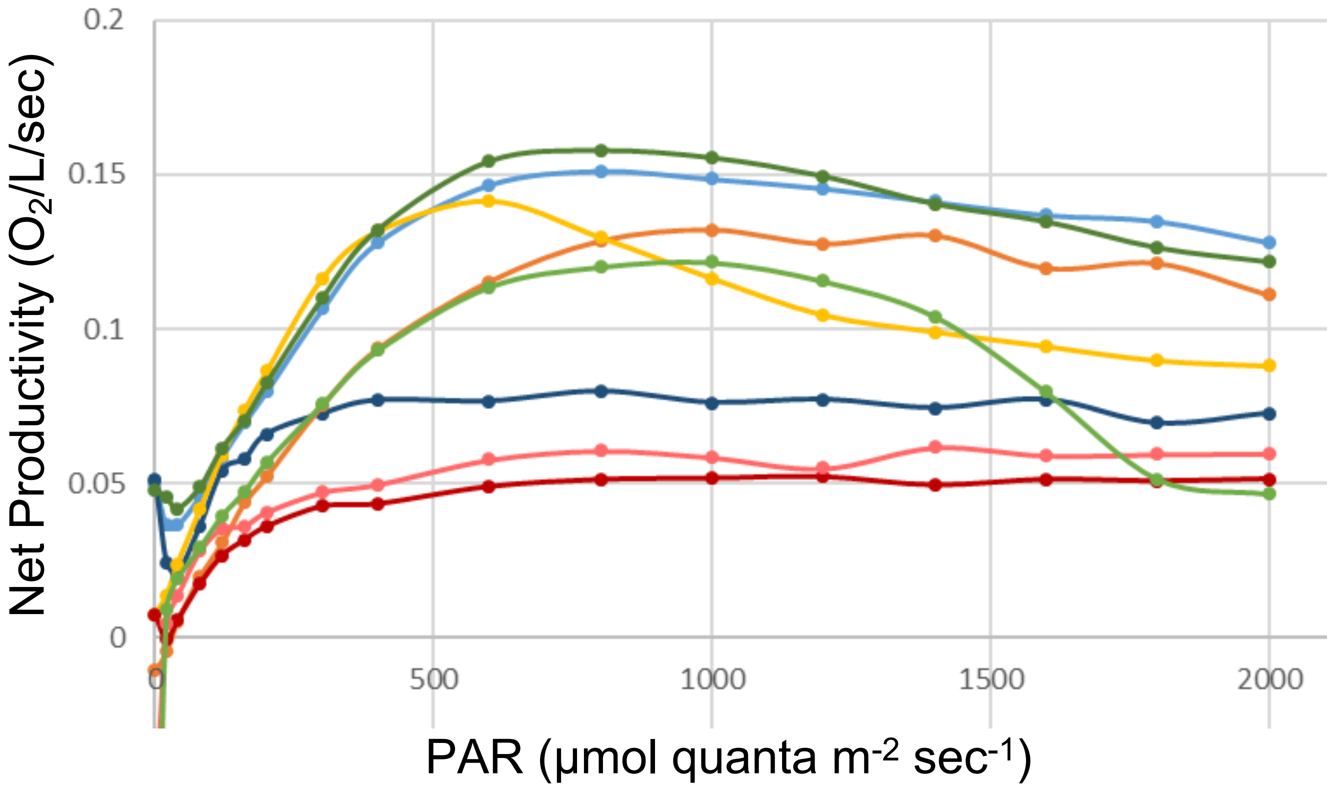
Photosynthetic performance for various strains



Progress

- Spectrally resolved light in ponds (last slide)
- Productivity related to light (this slide)

Next steps

- Integrated model and explore optimal solutions (i.e. depth, stocking) for a range of species

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Task 3 - Development of compact and efficient DAC units for micro-algal cultivation

Wei Liu
Molecule Works Inc.

DAC CO_2 skid for producing CO_2 at 25 g (DW algae) /day

1. First prototype testing system to be used at Duke for on-site CO_2 production has been designed and built with all the controls and auxiliary equipment
   - Computer-controlled for un-attended operation
   - Design CO_2 productivity of 1 kg/day (~300 scfm of air flow)
2. Delivery of Gen 0 of adsorption and heat exchanger (AHX) module – the core piece of equipment for the testing system has been delayed due to supply and logistical issues:
   - MoleculeWorks' proprietary designs
   - Several components are custom-designed and fabricated
   - All the parts are now ready for assembly of the module
3. The Gen 0 AHX module assembly and system debugging tests take about two months, and the milestone delivery will likely be delayed about one quarter.
4. Inhouse testing skid with manual operation has been built to develop Gen 1 AHX module as improvement to the Gen 0 module

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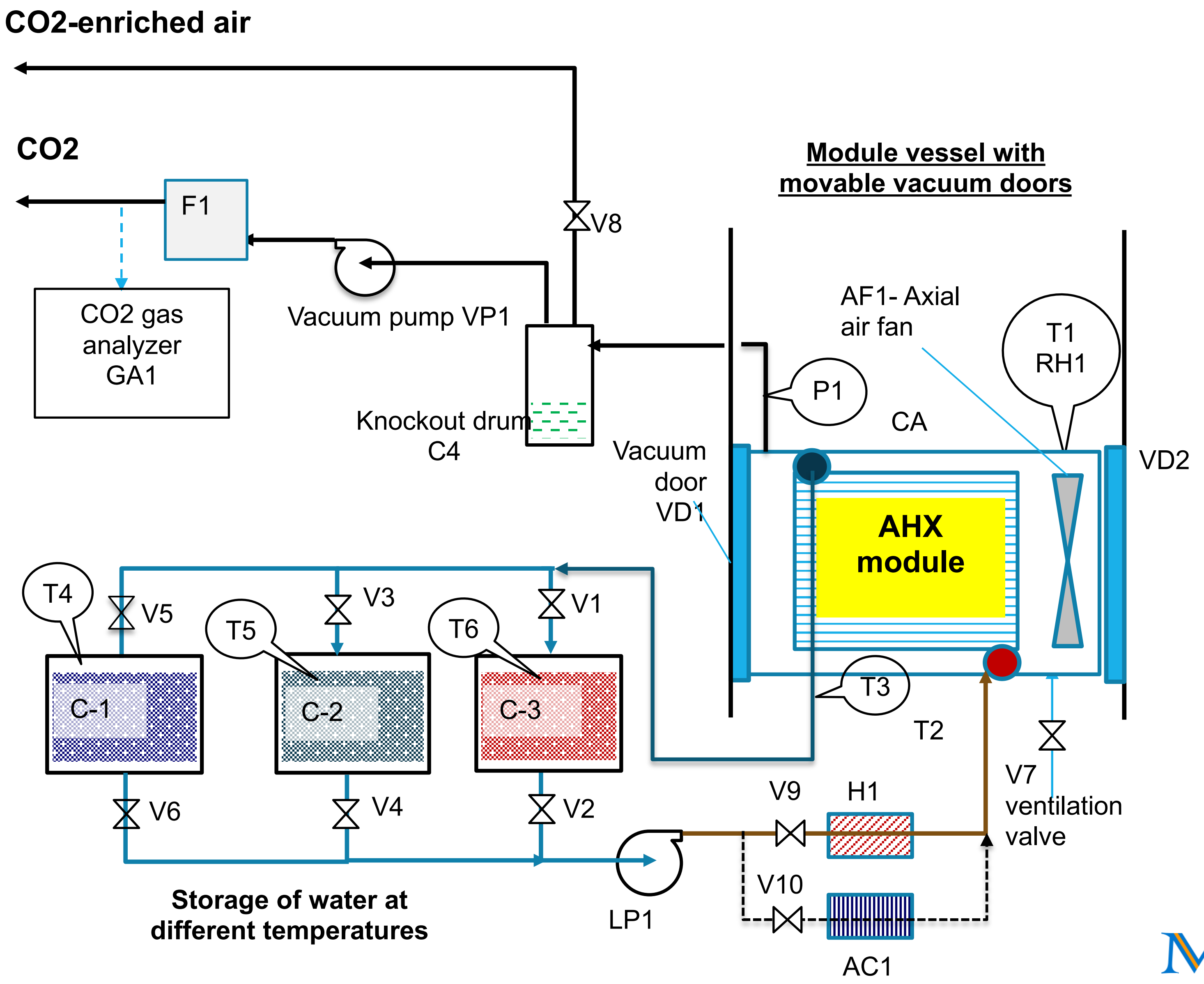
Process flow diagram of the DAC lab prototype unit based on selective CO_2 adsorption under ambient air conditions



1. Periodic switch between capture and regeneration operation
2. CO_2-enriched air is produced by heating the AHX module and sweeping desorbed CO_2 with air
3. Pure CO_2 is produced by heating the module and pulling desorbed CO_2 with vacuum pump
4. Hot and cold water are used for respective heating and cooling
5. Low-temperature and low-pressure system
6. No environmental emissions
7. MoleculeWorks AHX module enables CO_2 capture at high productivity and low energy consumption

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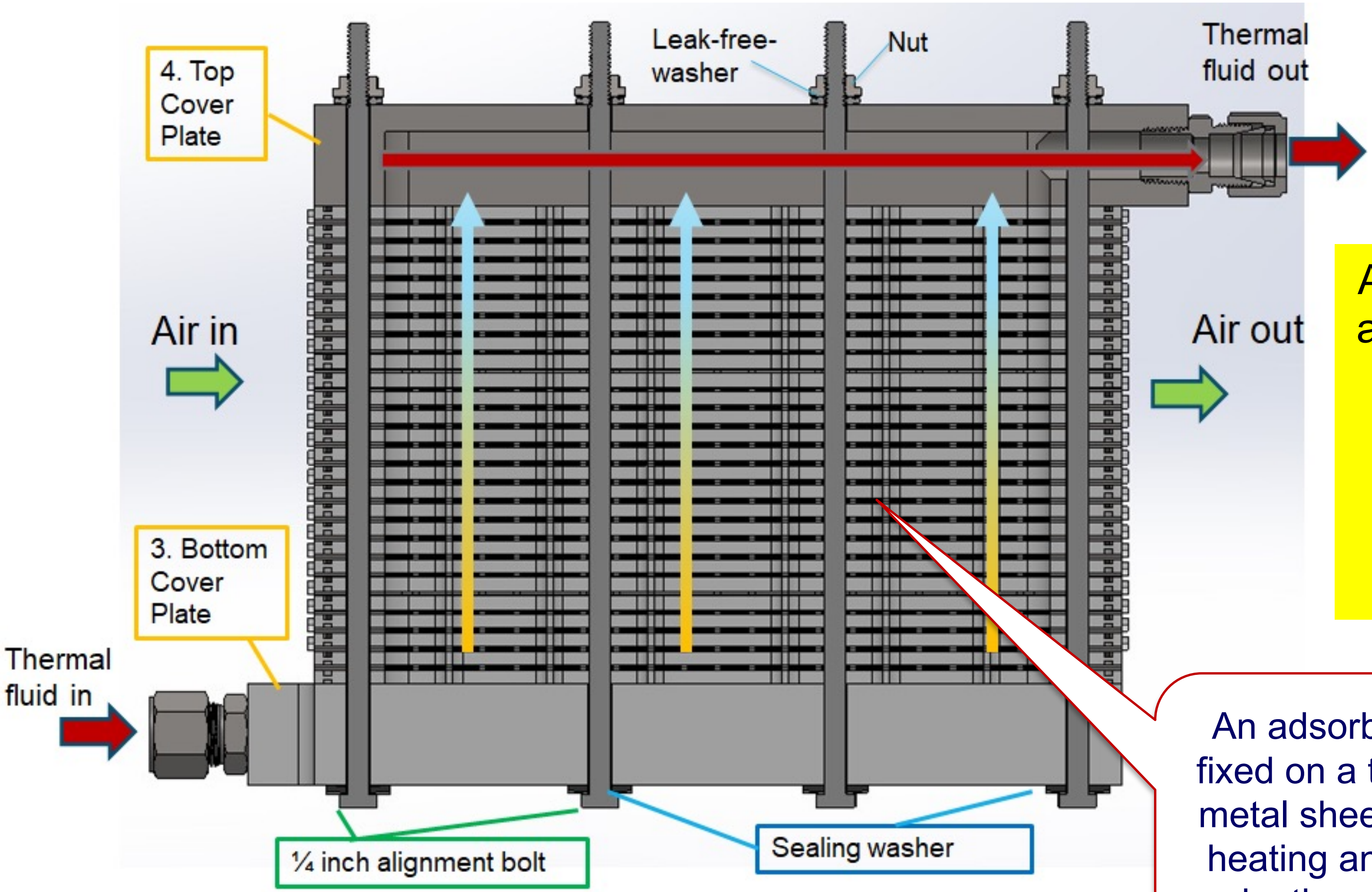
MoleculeWorks AHX module –Gen 0 design

Cut-open view of the module along the thermal fluid outlet slot centerline



Air flows over the adsorbent at high space velocity (50,000 v/v/h) and small pressure drop (~200Pa)

An adsorbent layer fixed on a thin dense metal sheet for rapid heating and cooling by thermal fluid

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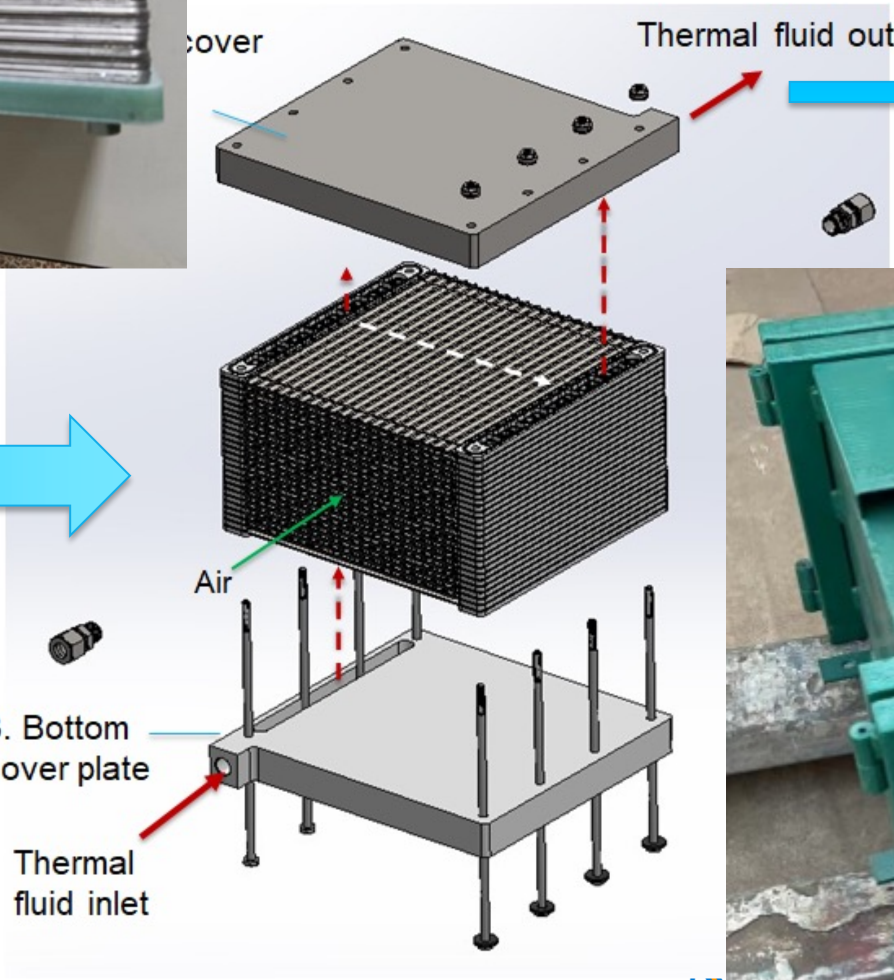
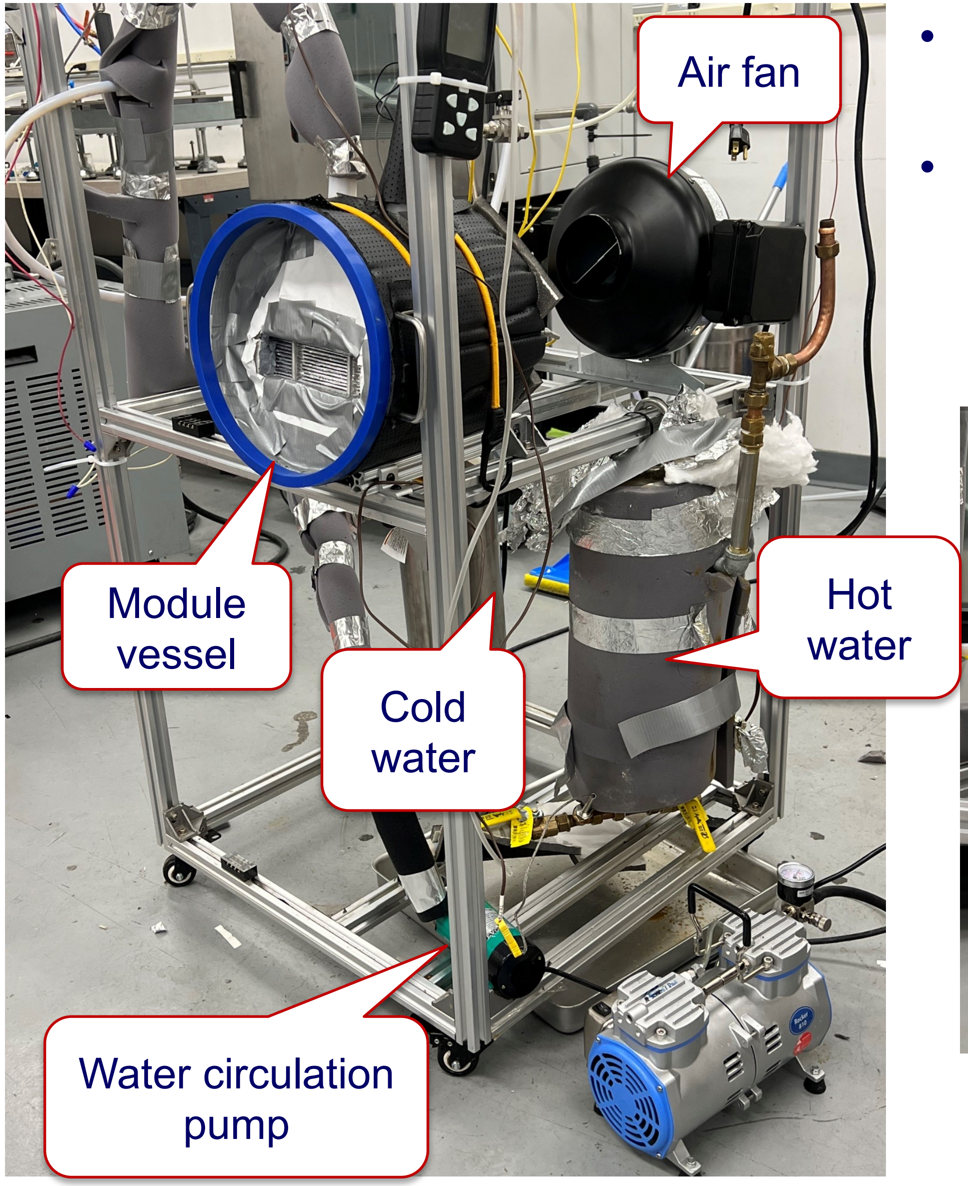
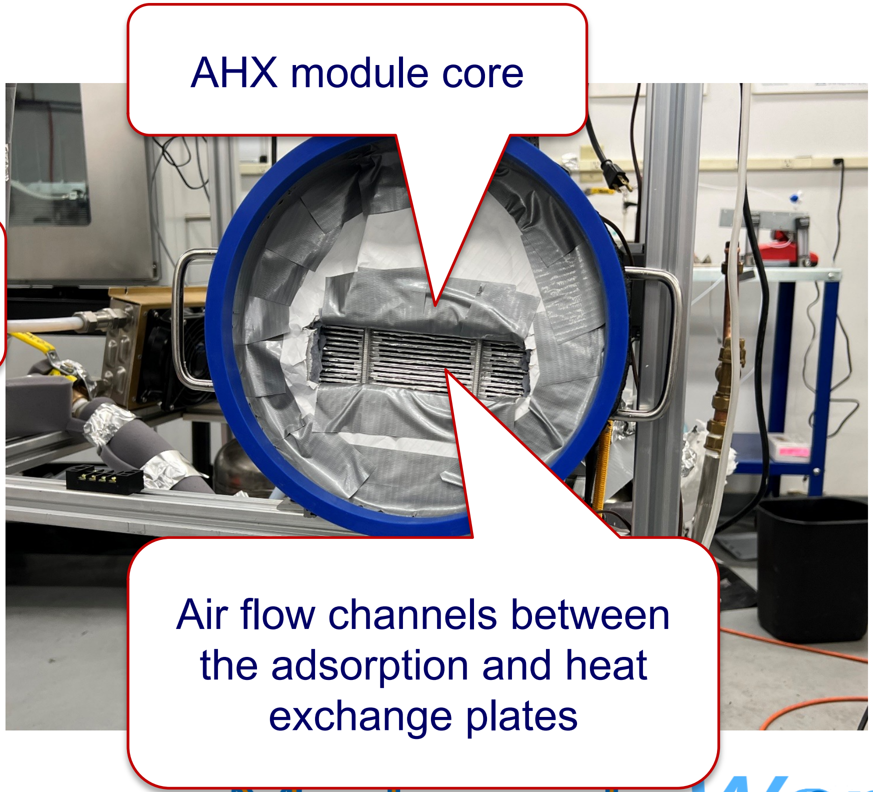
Fabrication of Gen 0 AHX module and vessel



Testing skid of Gen 1 AHX module (manual operation) – it's functional!



- The module can be quickly heated and cooled down by water, as designed
- The adsorbent can be regenerated with hot water to produce >20% CO_2



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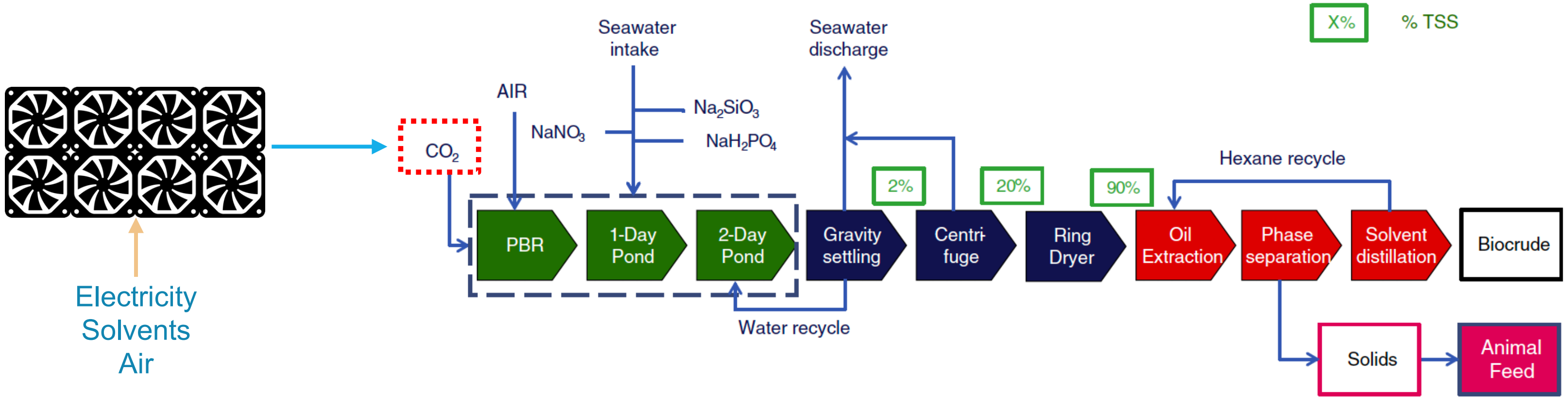
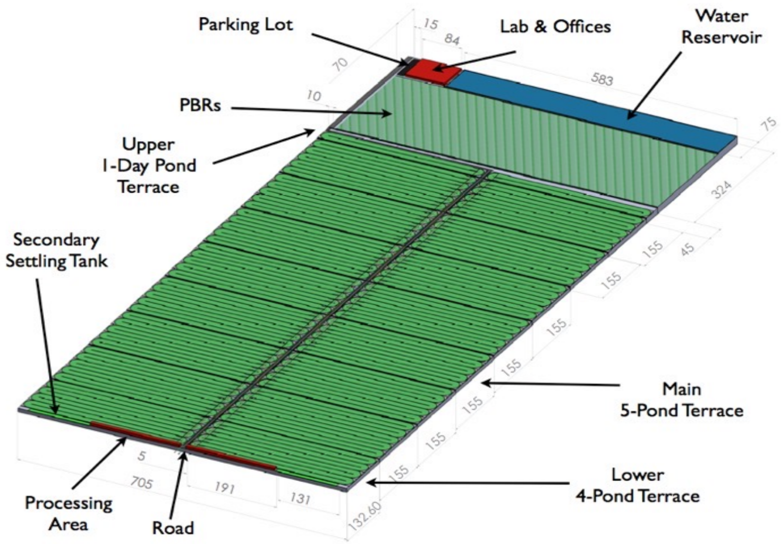
Task 5: ***TEA/LCA***

Modified Integrated Cultivation

- Updating model inputs to match CO_2 stream from Direct Air Capture



100-ha Algae Production Facility



Optimization of DAC / conversion

- Assess potential for improvement in Emissions/Cost with DAC CO_2

Scenario	GHGi (tCO2/tDW)	Biocrude MFSP ($/GGE)
50% CO2 from CaCO3, 50% CO2 from DAC	2.19	$ 13.11
50% Conventional CO2, 50% CO2 from DAC	4.02	$ 15.30
75% Conventional CO2, 25% CO2 from DAC	4.81	$ 15.90
Baseline Case	5.54	$ 16.51

Assuming baseline case yields achieved
Conventional CO_2 at $200/t CO_{2e}
CO_2 from DAC at $100/t CO_{2e}
CO_2 from $CaCO_3$ at $17/t CO_{2e}

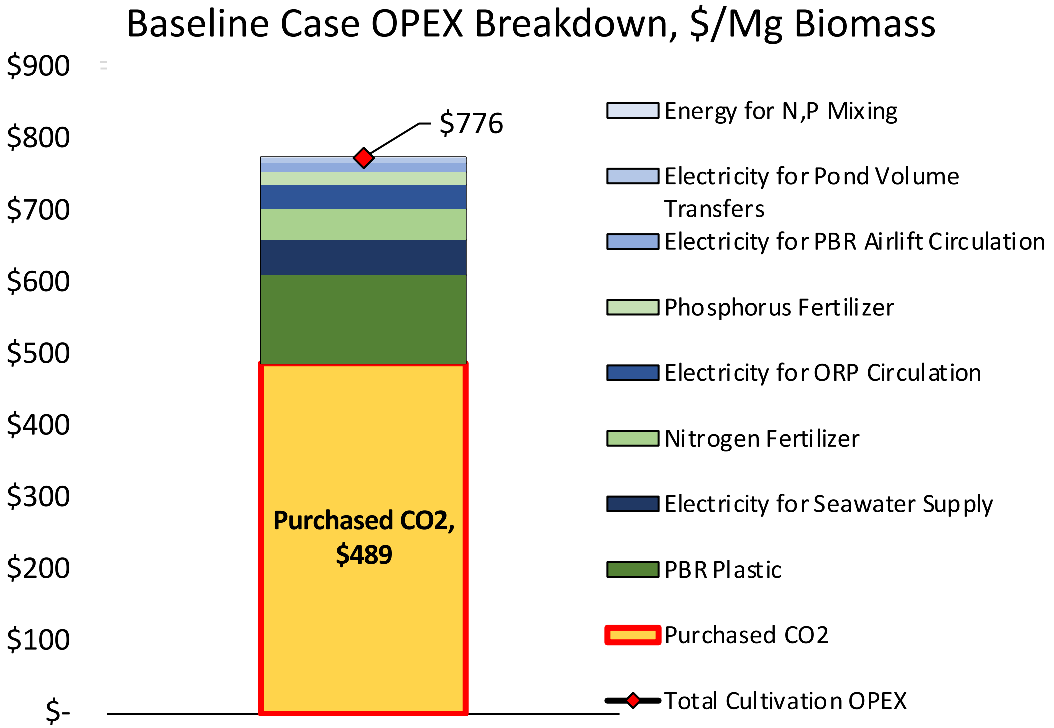
To be updated by Task 2 & 3 data

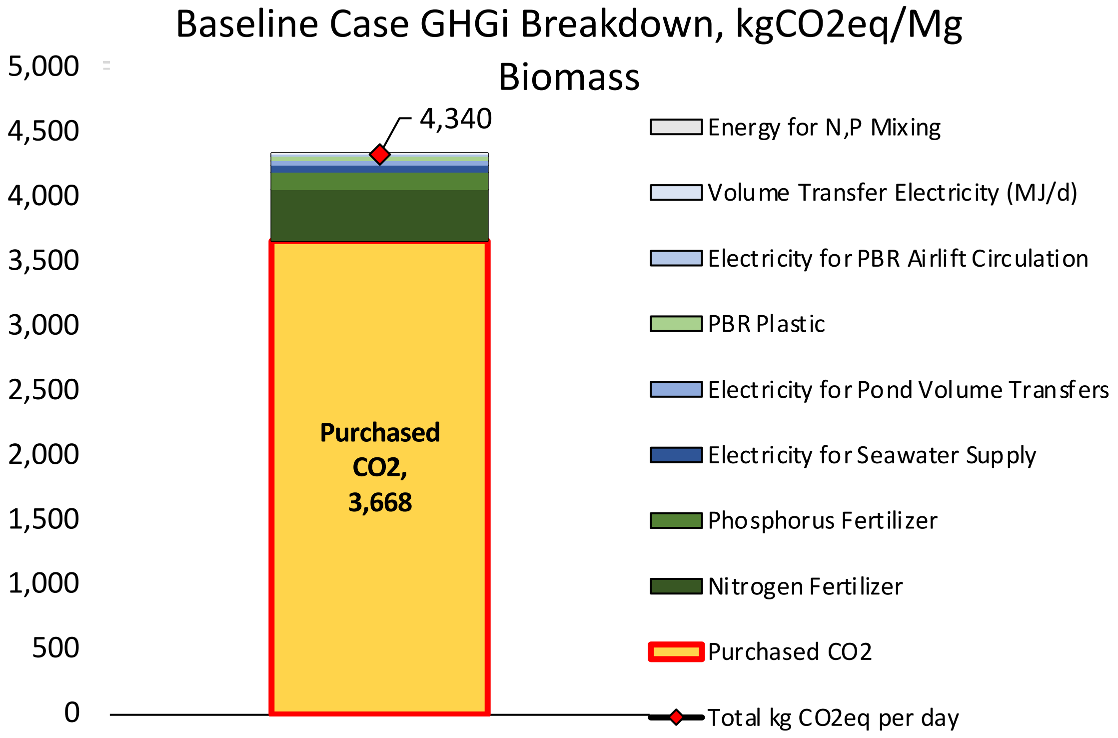
Task 5: ***TEA/LCA - Ongoing***

Techno-Economic Analysis and Life Cycle Assessment

- Target large portions of operational cost and emissions volume
  - Opportunity to reduce daily cost w/ DAC operation rather than piped CO_2, reduce emissions profile with DAC CO_2

- CO_2 is the largest contributor to OPEX and GHGi in baseline case

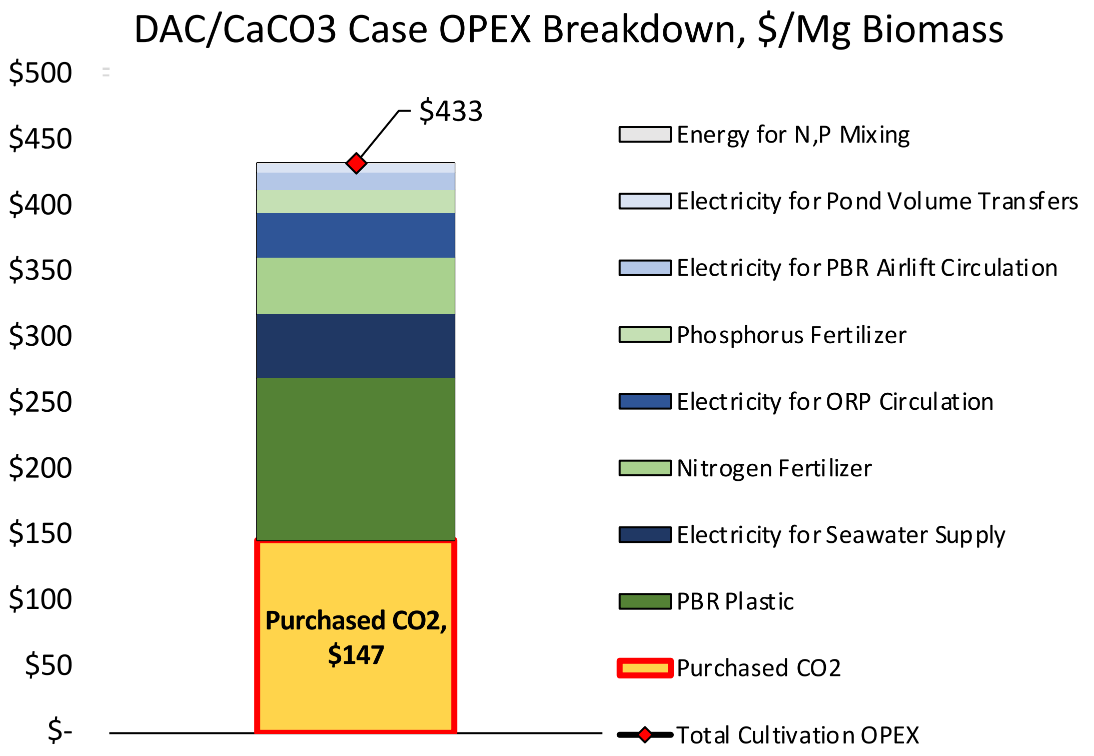


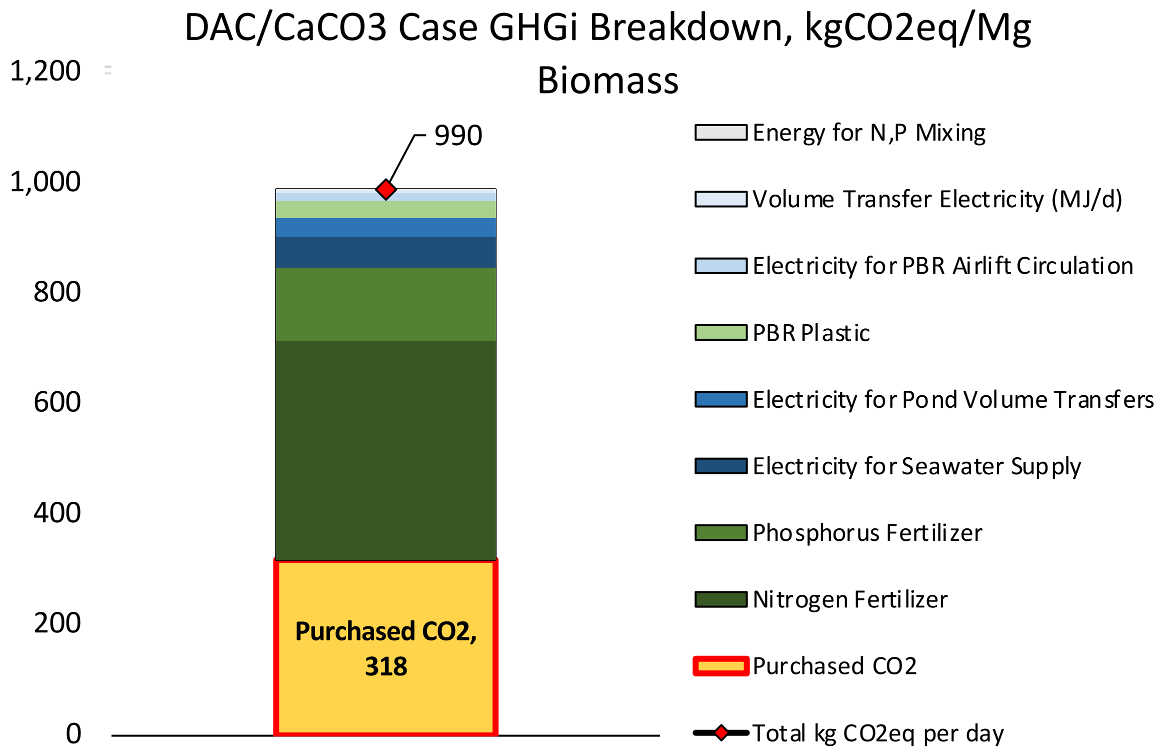


Task 5: ***TEA/LCA***

Techno-Economic Analysis and Life Cycle Assessment

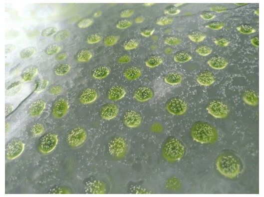
- CO_2 from DAC and $CaCO_3$ case shows substantial improvements in OPEX and GHGi





3 - Impacts

- **Economics of algae biofuels**
  - *Demonstration of reduced capex and opex makes algae-derived biofuels more economically feasible*
  - *Demonstration of enhanced co-product value lowers the price of biofuel*
- **CO_2 limits siting of economically feasible algae biofuel production**
  - *Demonstration of conversion of CO_2 to HCO_3 provides a CO_2 "integrator", expanding locations*
  - *Demonstration of uncoupling of CO_2 production (DAC) and algae greatly expands locations*
- **Results disseminated through peer-reviewed publications and other public presentations**



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MAGIC-ABCDE Summary

Task / Subtask	Q1	Q2	Q3	Q4	Q5	Q6	
Budget Period	BP1	BP2					
1 – Validation							
1.1 Validation	DP						Complete
2 – Strain Assessment and Cultivation							
2.1 strains screened for collagen/whey		m			DP		Strains acquired, screening ongoing
2.2 stocking density lab tests				m			Initial lab work done; testing of model outputs ongoing
2.3 modeling of cultivation re-design					DP		Model components complete; integrated model testing ongoing
3 –DAC CO_2 and conversion							
3.1 DAC CO_2 for lab testing			MS	DP			Lab unit complete
3.2 DAC CO_2 for ~1000 L scale					MS	m	Ongoing
3.3 CO_2 conversion system						m	Beta version complete; lab tests complete
4 – Demonstration							
4.1 algae on DAC+converted CO_2 in lab						DP	TBD
4.2 ~5000 L collagen/whey strains							
4.3 ~1000 L DAC+conversion in ponds							
4.4 ~1000 L modified cultivation design							
4.5 ~1000 L optimized stocking density							
5 – TEA/LCA							
5.1 modified integrated cultivation						DP	TBD
5.2 optimization of DAC / conv.						DP	TBD
5.3 geospatial extension			m				TBD
5.4 integration of large scale (4.2-4.5)							

Project Gantt Chart Task/sub task summary. Colored areas indicate primary activity peric
MS=SMART milestones, m=milestones.

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MAGIC-ABCDE (EE0009278) - Quad Chart Overview

Timeline (approved period)

- October 1, 2020
- December 31, 2022

	FY22 Costed	Total Award
DOE Funding	*$54,086*	$1,967,473
Project Cost Share	*$29,592*	$546,378 (22%)

TRL at Project Start: 2

TRL at Project End: 5

Project Goals

Strain assessment of key algae strains - identify strains with valuable co-products; measure/model marine microalgae to optimize cultivation and minimize costs
DAC / CO_2 conversion – demonstration of DAC & conversion of CO_2 to bicarbonate at multiple scales
Integrated system – demonstration of coupled DIC generation (ultimately from industrial CO_2) + algae growth
TEA/LCA – translation of laboratory and field findings to nth plant design, TEA/LCA of findings to quantify impacts on environment and economics

End of Project Milestone

Demonstrate enhanced algal growth on high DIC water at industrially relevant scale with a system that has improved environmental impact and economics

Funding Mechanism

DE-FOA-0002203, Algae Bioproducts and CO_2 Direct-Air-Capture Efficiency, 2020

Project Partners

B&D Engineering
Molecule Works, LLC

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Thank you

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http://www.duke.edu/~zij
http://www.ml.duke.edu/webcam/algae/

We're a team!

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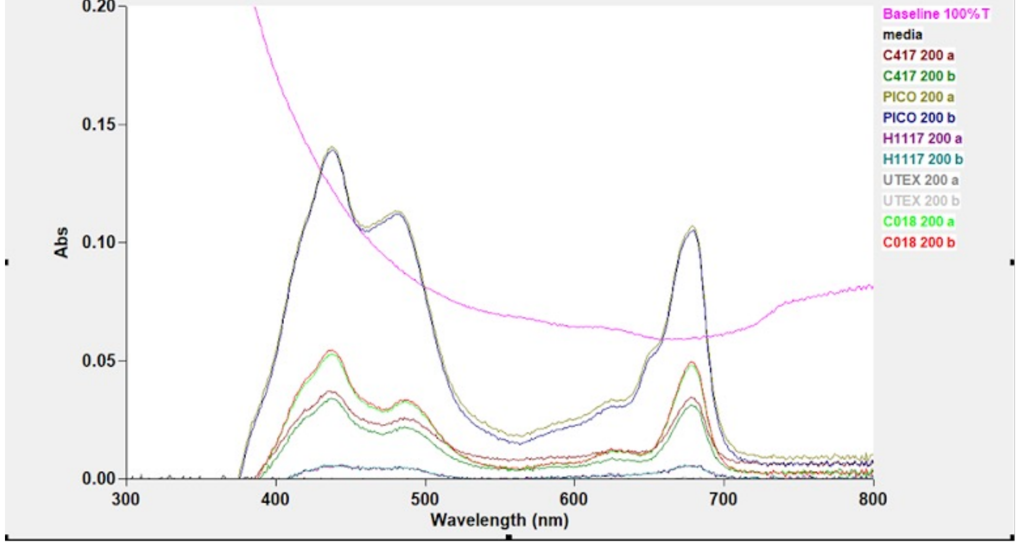
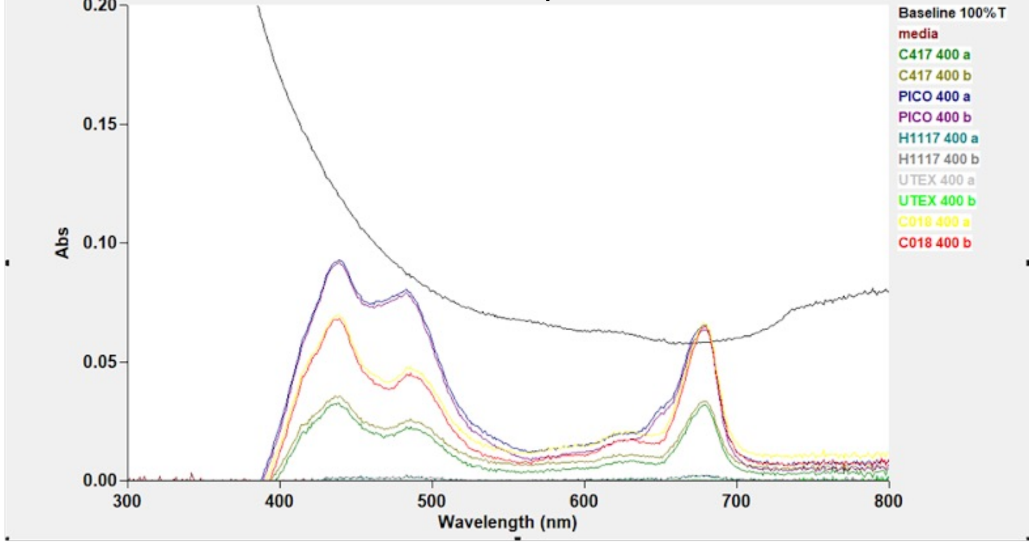
Additional Slides

High Resolution Spectral Absorption

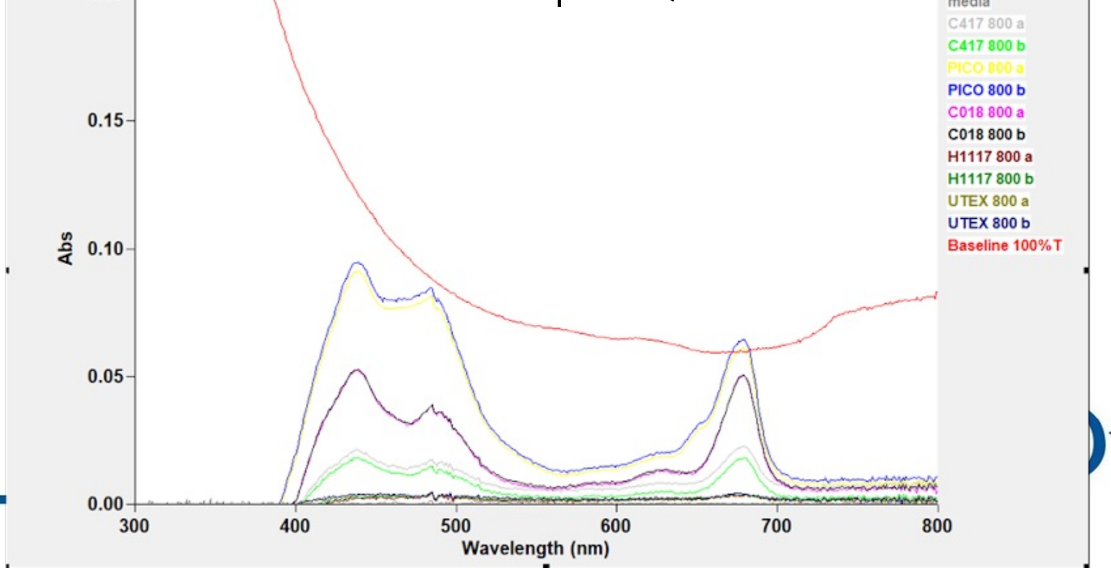
200 µmol Q m² sec⁻¹



400 µmol Q m² sec⁻¹



800 µmol Q m² sec⁻¹



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Publications

Doo SS, Kealoha A, Andersson A, Cohen AL, Hicks TL, Johnson ZI, Long MH, McElhany P, Mollica N, Shamberger KEF, Silbiger NJ, Takeshita Y, Busch DS (2020). The challenges of detecting and attributing ocean acidification impacts on marine ecosystems. ICES Journal of Marine Science. DOI: https://doi.org/10.1093/icesjms/fsaa094

Loftus SE, Hunt DE, Johnson ZI (2020). Reused cultivation water from a self-inhibiting alga does not inhibit other algae but alters their microbiomes. Algal Research 51: 102067. DOI: https://doi.org/10.1016/j.algal.2020.102067

Hall ER, Wickes L, Burnett LE, Scott GI, Hernandez D, Yates KK, Barbero L, Reimer JJ, Baalousha M, Mintz J, Cai W-J, Craig JK, DeVoe MR, Fisher WS, Hathaway TK, Jewett EB, Johnson Z, Keener P, Mordecai RS, Noakes S, Phillips C, Sandifer PA, Schnetzer A, Styron J (2020). "Acidification in the U.S. Southeast: Causes, Potential Consequences and the Role of the Southeast Ocean and Coastal Acidification Network." Frontiers in Marine Science 7. https://doi.org/10.3389/fmars.2020.00548

Marra JF, Barber RT, Barber E, Bidigare RR, Chamberlin WS, Goericke R, Hargreaves BR, Hiscock M, Iturriaga R, Johnson ZI, Kiefer DA, Kinkade C, Knudson C, Lance V, Langdon C, Lee Z-P, Perry MJ, Smith WO, Vaillancourt R, Zoffoli L (2020). A database of ocean primary productivity from the 14C method. Limnology and Oceanography Letters. https://doi.org/10.1002/lol2.10175

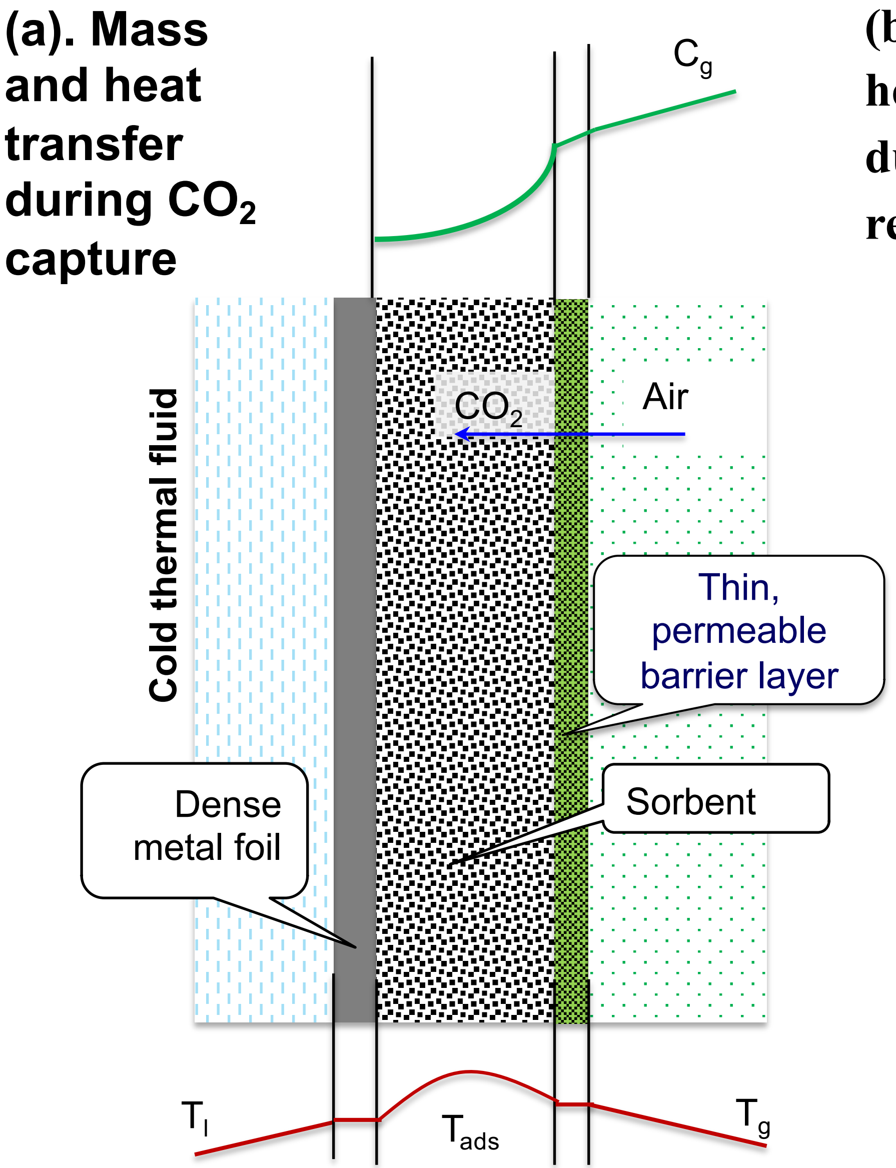
Patents, Awards, and Commercialization

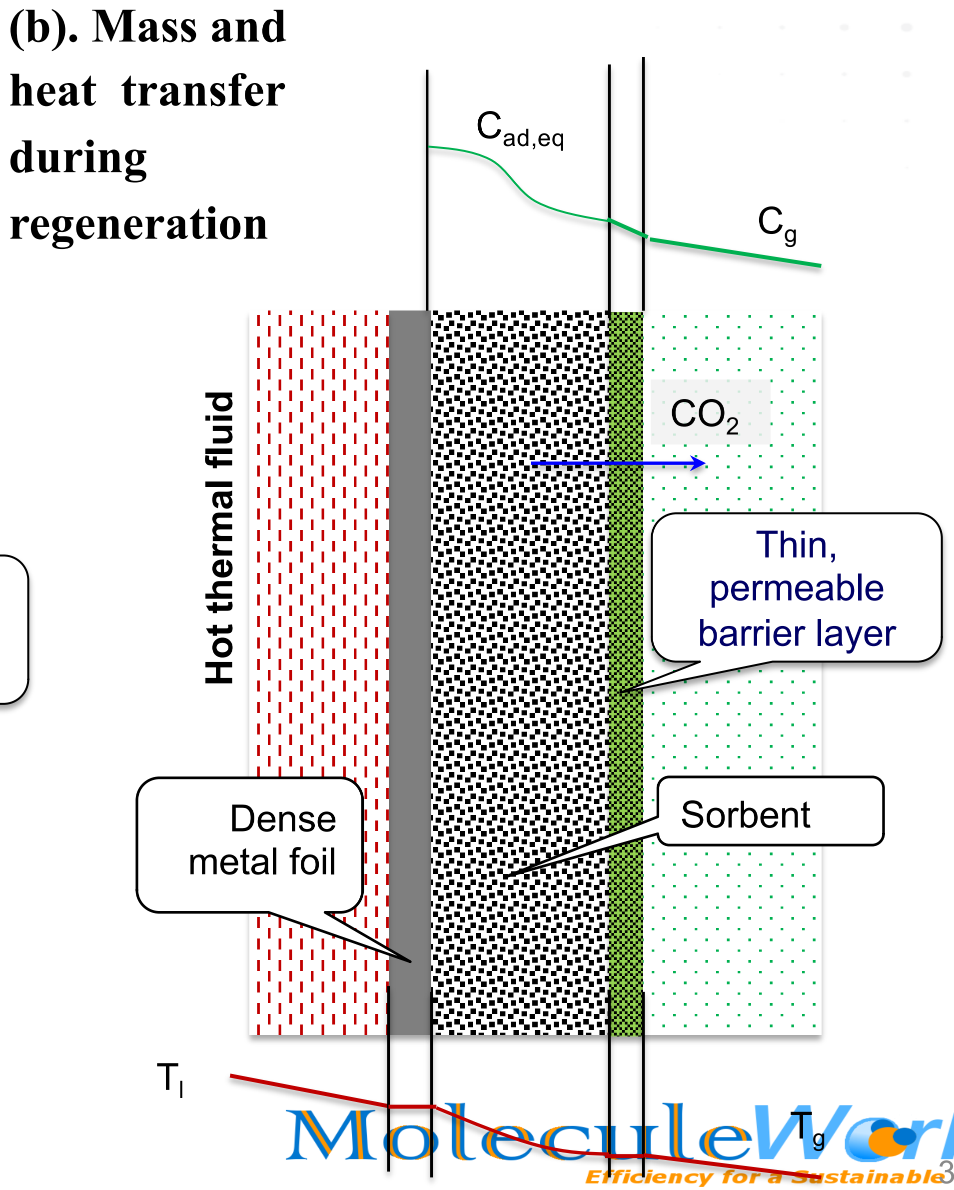
No patents have yet been applied for based on the work supported by DOE.

Algae Biomass Organization Mid-Career Award: PI - Zackary Johnson

All primary results from this project are being published in the open, peer-reviewed literature. The publications from this project – cited above – provide a comprehensive and detailed analysis of commercialization potential. This information will be available to anyone with access to the open literature.

Working principle of adsorption/heat exchange (AHX) design for rapid CO_2 capture and regeneration





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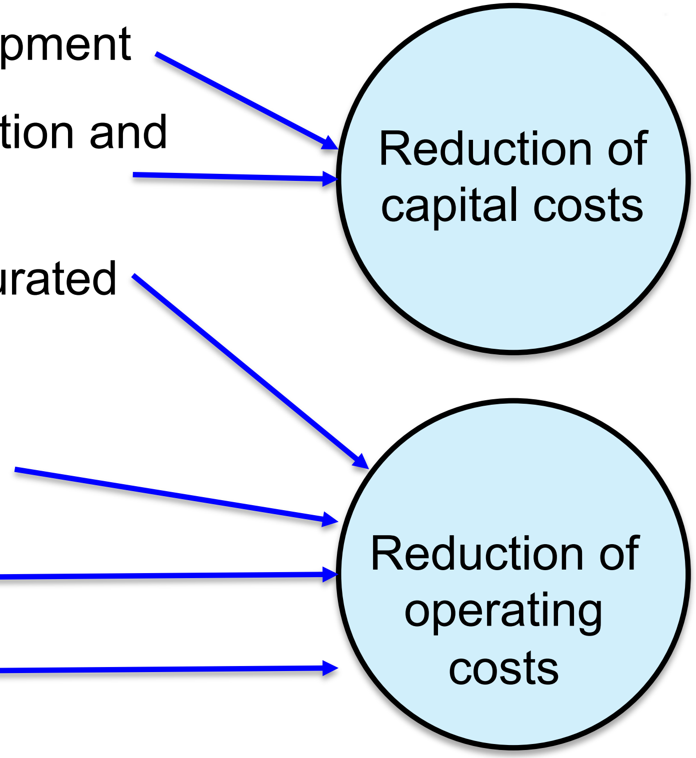
AHX technology innovations and impacts

1. Utilize low-pressure and low-temperature equipment
2. Enable high CO_2 productivity via rapid adsorption and regeneration operation
3. Utilize low-quality heat for regeneration of saturated sorbent and release of CO_2
4. Allow large volume of air to pass through the adsorption channel at low pressure drops
5. No volatile solvents involved.
6. No or minimal water consumption



Continuing improvements to achieve commercial production cost less than $100/ton of CO2

The AHX module design and adsorbent material performances are two determining factors to the cost

AHX module prototype used for invention demonstration 0.8 m2 work area for 300 NL/min air flow

Gen 0 design: 2X reduction to weight and cost

Gen 1 design: 2X reduction to weight and cost