DOE Bioenergy Technologies Office (BETO) 2021 Project Peer Review

Direct Air Capture of CO_2 and Delivery to Photobioreactors for Algal Biofuel Production

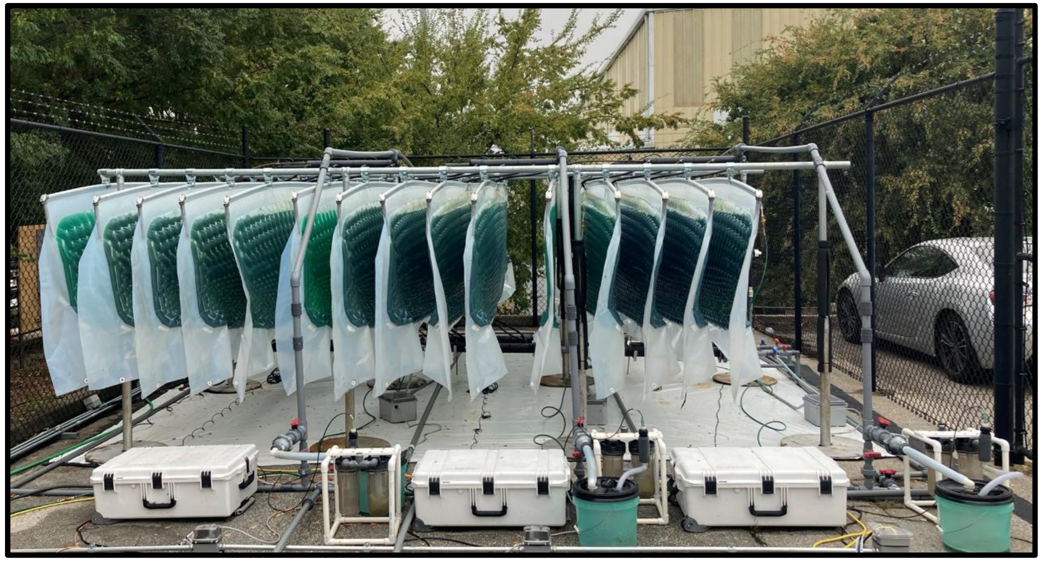
March 23, 2021
Advanced Algal Systems

Christopher W. Jones
Georgia Tech Research Corporation
Georgia Institute of Technology

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

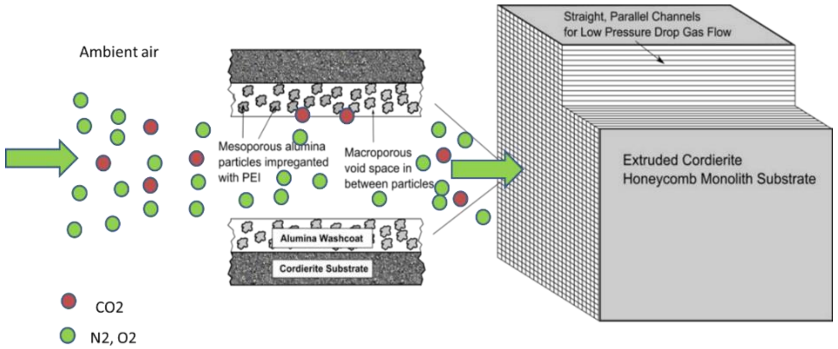
Project Overview

- *Global Thermostat, LLC,* has developed technology for CO_2 extraction from air.
- *Algenol Biotech* has developed ethanol-producing cyanobacteria using enclosed, polymeric photobioreactors for outdoor algae cultivation.
- We seek to marry CO_2 capture from air with algae growth in PBRs.



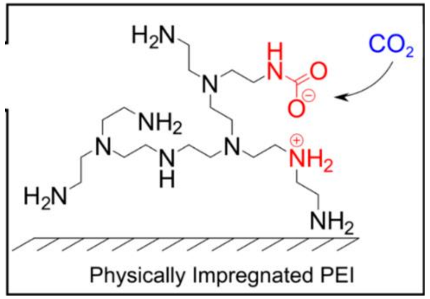
Global Thermostat Process & Materials Platform Addresses Five Key Challenges to Enable Low-Cost DAC

1. Moving Large Air Volumes Efficiently



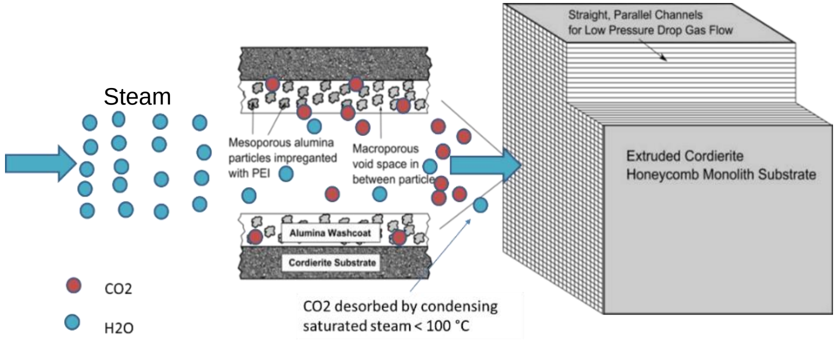
Honeycomb monoliths significantly outperform all other designs, enabling low pressure drop and minimum energy cost

2. Capturing CO_2 Selectively at 400 ppm



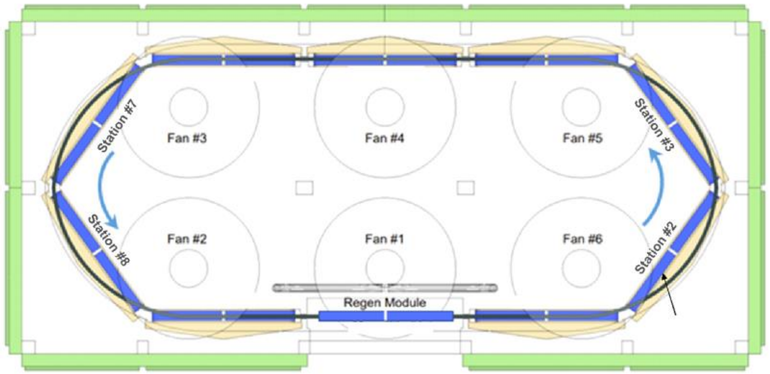
Amine-based polymers, incorporated in proprietary coatings, yield selectivity, capture efficiency, and compatibility with honeycomb monolith approach

3. Energy Efficient Regeneration of Captured CO_2



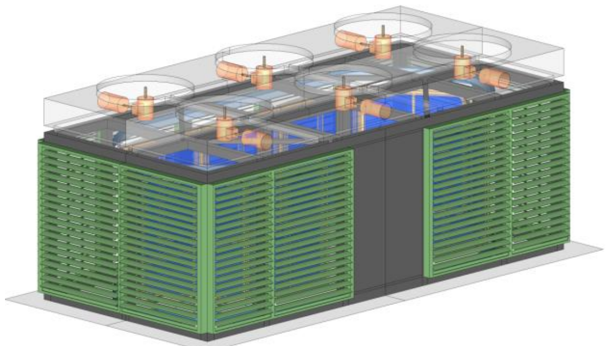
Temperature-Vacuum Swing Absorption (TVSA) with steam as direct phase-change heat transfer fluid

4. Capital Utilization Efficiency



Process and mechanical movement design enable multi-bed adsorption configuration serviced by one regen module

5. Design for Continuous Improvement



Base capital design capable of receiving new and future generations of improved adsorbent materials to regularly maximize capture capacity and extend plant capital life.

Global Thermostat

Project Overview

- Objectives: 1) Advance direct air capture (DAC) technology as a location agnostic CO_2 source. 2) Couple DAC with algae growth in PBRs to reduce siting constraints and/or the carbon footprint of algal biofuel production.

- State-of-the-art: A) Algenol PBRs are fed CO_2 from flue gas from heat/power production or commercial sources. B) Global Thermostat DAC technology developed as stand-alone technology.

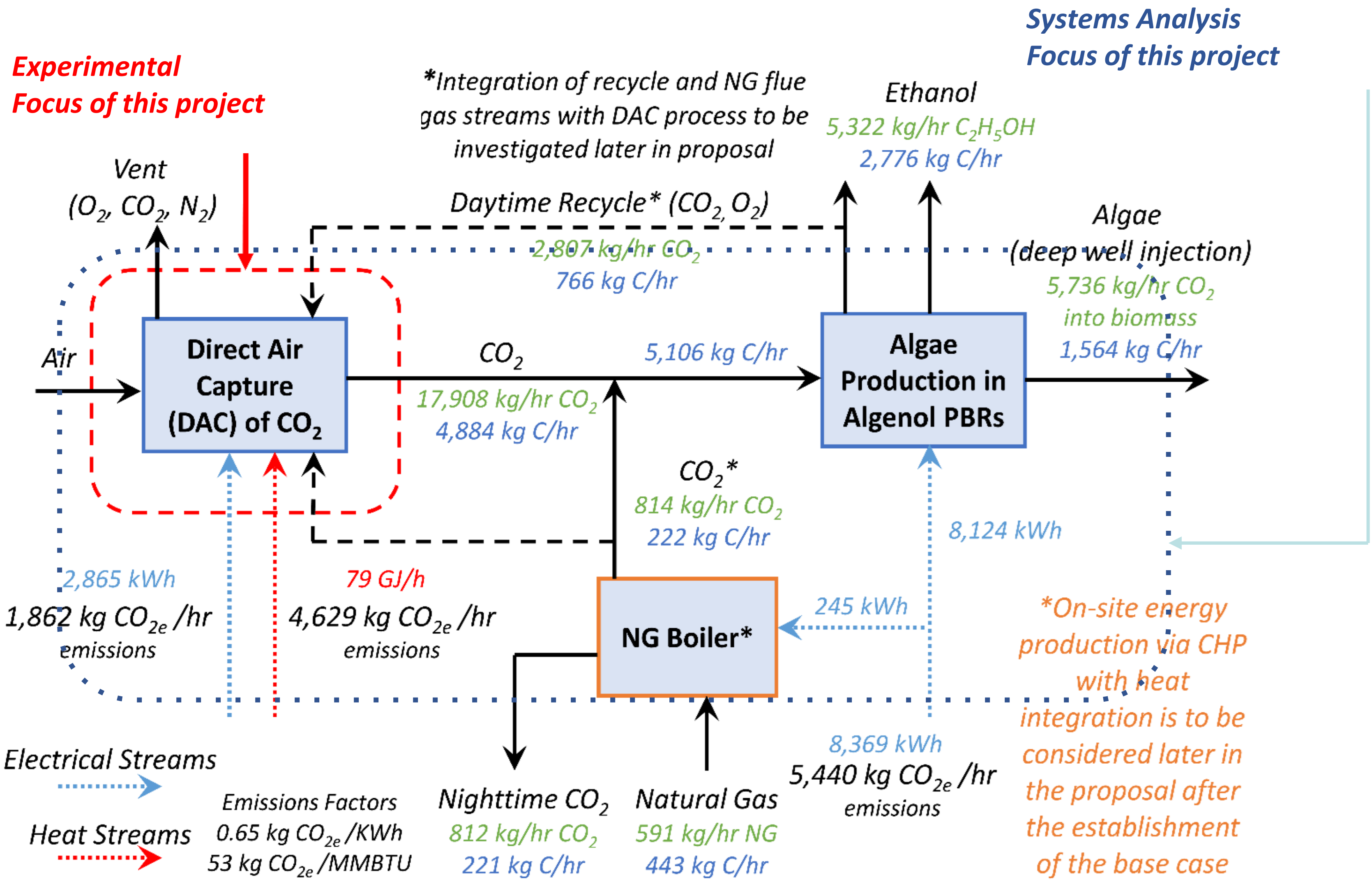
Project Overview

- Opportunity: Coupling DAC and algae production in PBRs could provide benefits to both technologies by integrating heat/mass streams associated with each technology.

- Importance: 1) DAC technology, if advanced to reduce costs, could be critical to local CO_2 supplies in locations with current high costs.

  2) DAC technology could one day produce negative CO_2 emissions if coupled with geologic storage

Project Overview



Quad Chart Overview

Timeline

- April 2019
- September 2022

Includes 6 month no cost extension

	FY20 Costed	Total Award (through BP2)
DOE Funding	$718,220	$957,064
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Barriers addressed

- Aft-A. Biomass Availability and Cost
- Aft-B. Sustainable Algae Production
- Aft-M: Integration and Scale-Up

Project Partners*

- Global Thermostat
- NREL
- Algenol Biotech

Project Goal

Develop a Direct Air Capture (DAC) system comprised of solid amine monolith adsorbents that will integrate with existing photobioreactor (PBR) technology to deliver at least 20% of the required CO_2 for algae cultivation.

End of Project Milestones

- Integration of DAC system with PBRs and sorbent/process improvements that allow production of ≥25 g CO_2/h.
- TEA/LCA modeling integrates DAC+PBR systems to improve energy efficiency of overall process and decrease cost of CO_2 production. Final TEA and LCA recommend the two most efficient combinations of an Algenol PBR and the Global Thermostat DAC technology, (i) most effective experimentally demonstrated mode, and (ii) most efficient combination derived from TEA/LCA modeling.

Funding Mechanism

DOE-FOA-0001908
05/03/2018

1 – Management

Partner/PI	Role(s)	Tasks
Project Director: Christopher Jones, Georgia Tech		
Direct Air Capture (DAC) of CO_2		
Georgia Tech/Jones	DAC experimentation	2,3,6,7,8,11,12,13
Global Thermostat/Ping	DAC process knowhow & data	2,3,6,7,8,11,12,13
Algae Cultivation		
Georgia Tech/Chen	Algae experimentation	8,13
Algenol Biofuels/Chance	PBR supply, operation, data, models	8,13
Technoeconomic (TEA) & Lifecycle Analysis (LCA)		
NREL/Tan	TEA analysis	4,9,14
Georgia Tech/Thomas	LCA analysis	5,10,15

1 – Management

Key Challenge:

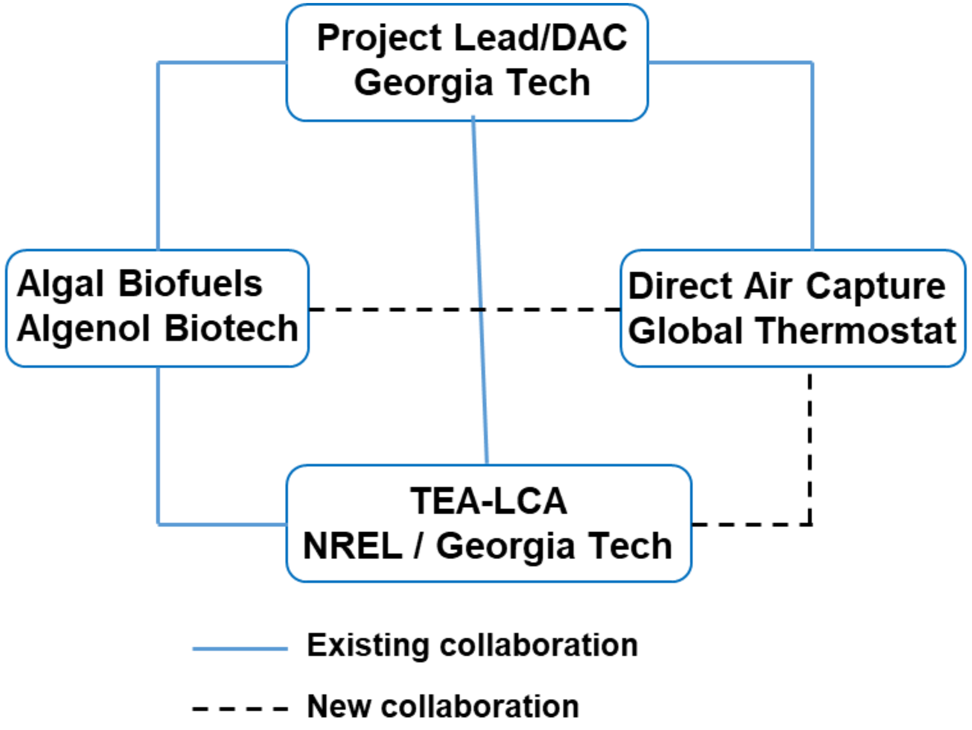
- Algenol Biotech informs team in summer 2019 of intention to withdraw to a consulting role only.
- Original plan had them operating PBRs in Florida, with Georgia Tech shipping the DAC unit to Fort Myers twice in the project.

Risk Mitigation:

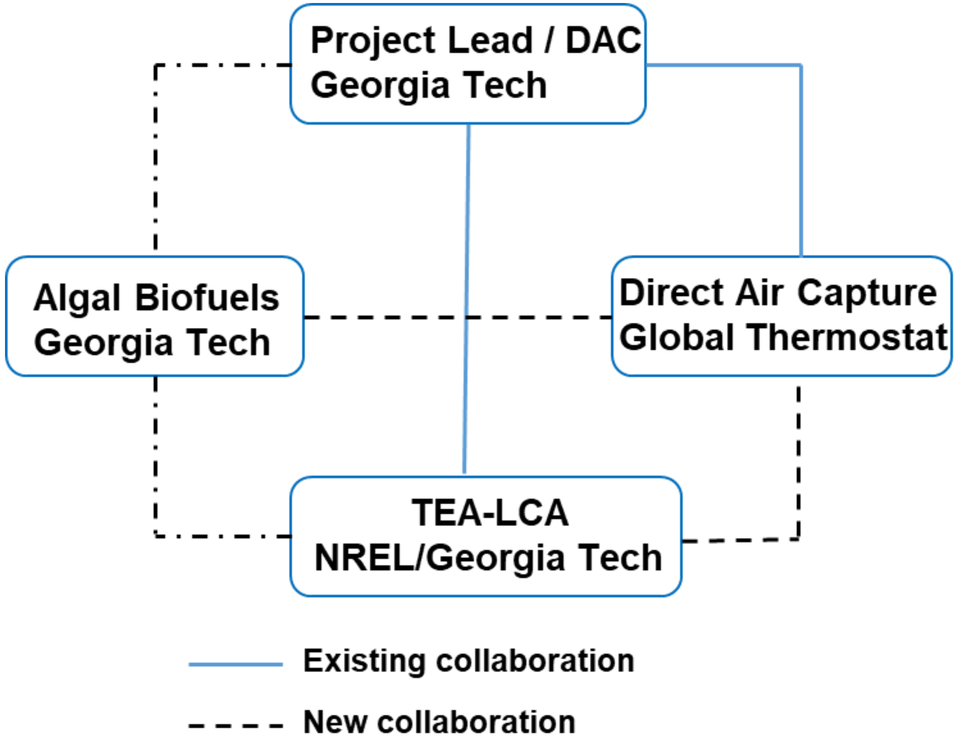
- Reduce Algenol's budget, shift to Georgia Tech and add new PI, Yongsheng Chen, with expertise in algae cultivation.
- Algal cultivation now conducted immediately adjacent to DAC research.
- This change, plus global pandemic, led to 6 month NCE – project on track.

1 – Management

Original Plan, as Proposed



Current Team & Path



1 – Management

GIT = Georgia Tech
Global = Global Thermostat
NREL = NREL
Algenol = Algenol

Christopher W. Jones, Project Director

Direct Air Capture Team
Christopher W. Jones
Eric W. Ping
Miles Sakwa-Novak
Ron Chance
Yanhui Yuan
Karl Olsen
Cassandra Hertz
Dong-Kyu Moon (Postdoc)
Juliana Carneiro (Postdoc)

Algae Team
Yongsheng Chen
Thomas Igou (PhD student)
Ron Chance (former Algenol)
Yanhui Yuan (former Algenol)
Cassandra Hertz (former Algenol)
Bill Porubsky

TEA/LCA Team
Eric Tan
Valerie Thomas
Kylee Harris
Shavonn D'Souza (MS student)
Jaden Johnston (PhD student)

Communication:
1) Monthly DAC team videoconferences
2) Monthly Full Team videoconferences
3) Former Algenol employees hired by Global Thermostat

1 – Management / 2 – Approach

Algae Cultivation

- Demonstrate growth of Arthrospira platensis (AB2293) in PBRs w/bottled CO_2
- Demonstrate growth AB2293 w/CO_2 from DAC system.
- Demonstrate growth of AB2293 w/CO_2 from optimized DAC system.

DAC

- Global Thermostat and Georgia Tech design and build a portable DAC system.
- Georgia Tech and Global Thermostat design/prepare oxide monoliths with amine-based CO_2 binding sites
- Georgia Tech and Global Thermostat stabilize amine sorbents towards deactivation by oxidation
- Global Thermostat provides NREL and Georgia Tech with key data for TEA/LCA
- DAC experimentation and TEA/LCA suggest ways to efficiently integrate DAC/PBRs
- DAC/PBR combination allows for consistent, effective production of algae in extended outdoor cultivation.

TEA/LCA

- Assessment tools continuously provide insight into DAC/PBR integration approaches.

Blue = Remains to be completed.

1 – Management

- Risks:

<u>Anticipated</u>
1) Company bankruptcy
2) Delayed hiring of personnel
3) Delayed delivery of components
4) DAC system construction slow
5) Amine impurities from DAC harm algae
6) Sorbent oxidation mitigation strategy fails
7) Poor communication with team

<u>Unanticipated</u>
8) Team member withdraws from program

Green = Managed
Blue = Remains to be evaluated.

- Management

~~1) Company bankruptcy~~
~~2) Delayed hiring of personnel~~
~~3) Delayed delivery of components~~
4) DAC system construction slow – Global/GT invested additional resources
5) Amine impurities from DAC harm algae – monitor DAC system for amine loss
6) Sorbent oxidation mitigation strategy fails – multiple paths, one successful
7) Poor communication with team – regular meeting schedule

<u>Unanticipated</u>
8) Team member withdraws from program – reduced Algenol role, add GT PI (Chen)

2 – Approach

Key Challenges

- Design, build, automate DAC system
- Identify heat/mass streams in DAC and algae cultivation technologies that could offer synergy via integration.
- Develop strategy for extending lifetime of DAC sorbents via oxidative degradation mitigation.
- Demonstrate successful integration of algae cultivation with CO_2 capture from air.

BP2 Go/No-Go Decisions

- DAC system with baseline amine sorbent monoliths deliver at least 20 g CO_2/hr (11 L/hr) when using air from the immediate, indoor environment and using optimized cycle conditions. *Demonstrated functional, mobile DAC system for integration with PBRs. CO_2 delivery rate sized for Algenol PBR array.*

- TEA/LCA quantifies reduced potential cost (~15% or better reduction) and increased material and energy benefits of heat and mass integration of DAC and Algenol processes, as compared to what can be achieved by DAC technology development independently. *Analyses suggests tangible benefits may arise from DAC/PBR integration.*

3 – Impact

Anticipated Improvements in State-of-the-Art

- Advance DAC technology, independent of biofuel production, by enhancing the lifetime of commercially relevant supported amine monolith adsorbents.

- Advance algal biofuels by reducing the cost and/or carbon intensity of the fuel, while also allowing for greater biorefinery siting by removing the need to co-locate with large flue gas sources.

Impact on Technology and Society

- Global Thermostat is commercializing DAC technology at various scales for CO_2 supply and as a negative emissions technology to address climate change.
- Largest uncertainty in TEA for DAC is lifetime of the sorbent, a parameter specifically targeted in this project.
- Proven coupling of DAC with Algenol PBR technology facilitates reduction of algae production costs and/or reduced carbon footprint.

3 – Impact

Dissemination Strategy

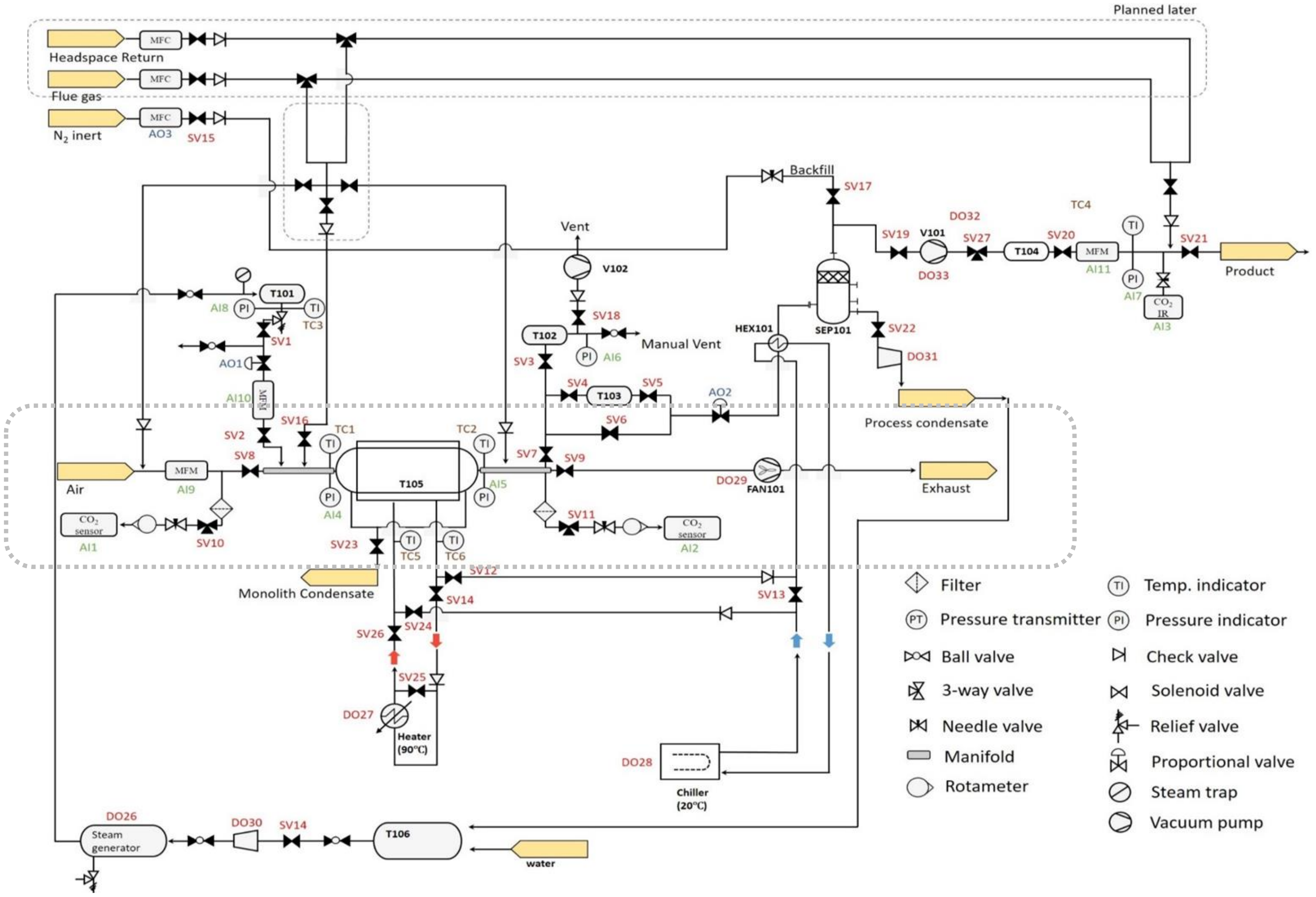
- Georgia Tech (Jones) & Global Thermostat have published ~6 collaborative papers prior to project
- Georgia Tech (Thomas) & Algenol have previously published algal biofuel LCA analyses.
- Team intends to publish non-proprietary science and technology results from this project.

Technology Commercialization

- Algenol has commercialized algae production for specific specialty markets.
- Global Thermostat is commercializing DAC technology via modular units that may be parallelized by scaling out.
- Global Thermostat has partnered with ExxonMobil via a JDA to explore scale-up of the DAC technology

DAC

4 – Progress and Outcomes



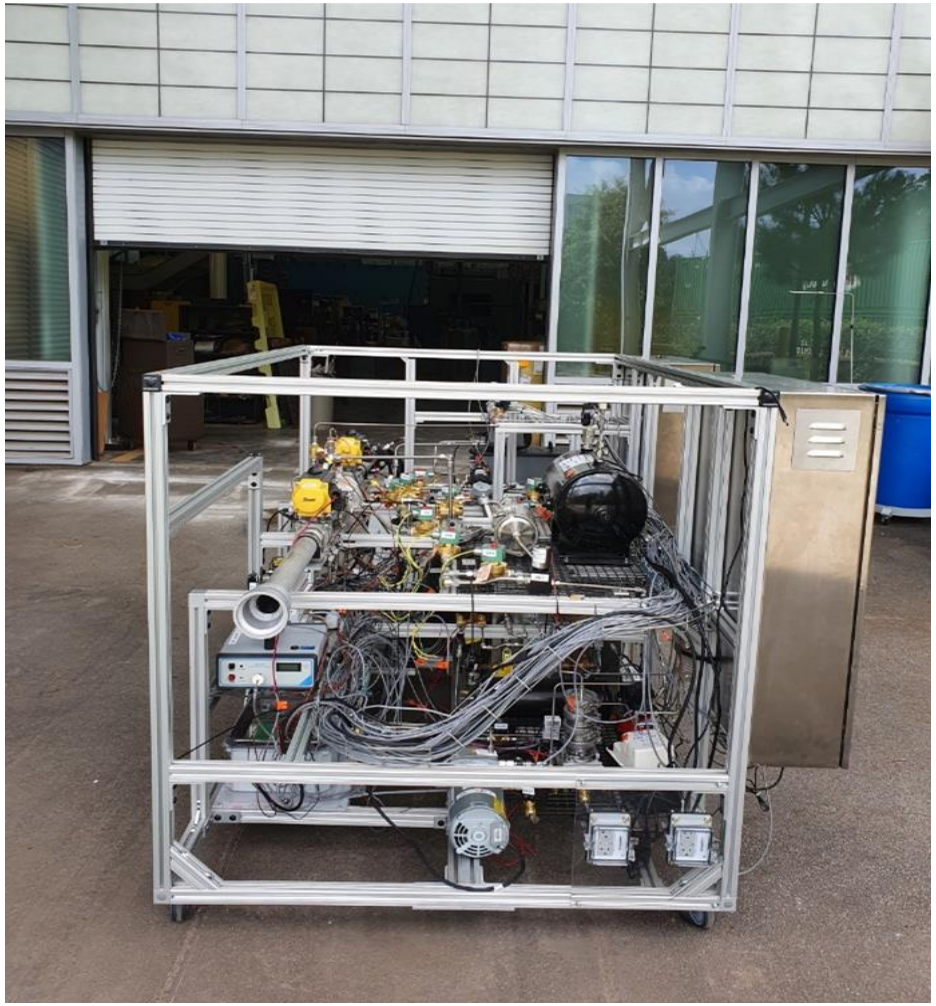
PNID of DAC System

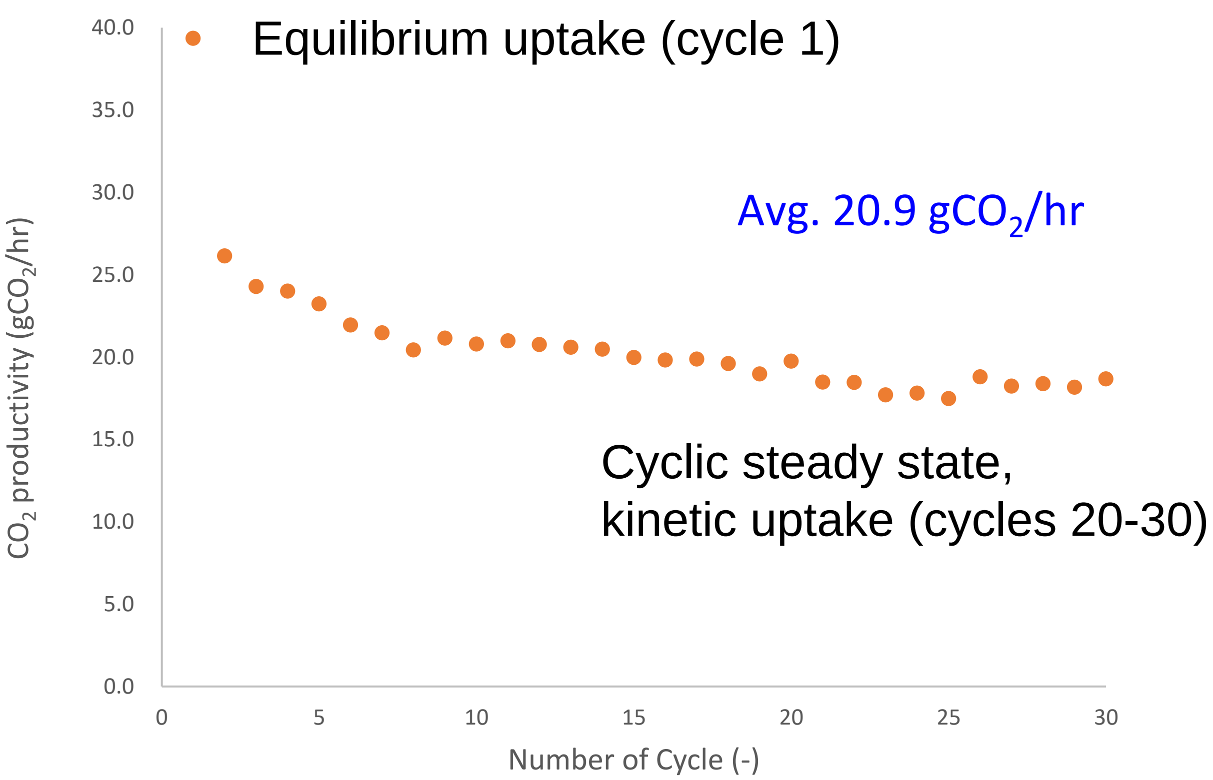
- Air drawn through monolithic sorbent bed by fans
- Heating/cooling fluid jackets monolith
- Direct steam injection through monolith quickly effects CO_2 desorption
- Small scale system models adsorption & desorption steps well

DAC

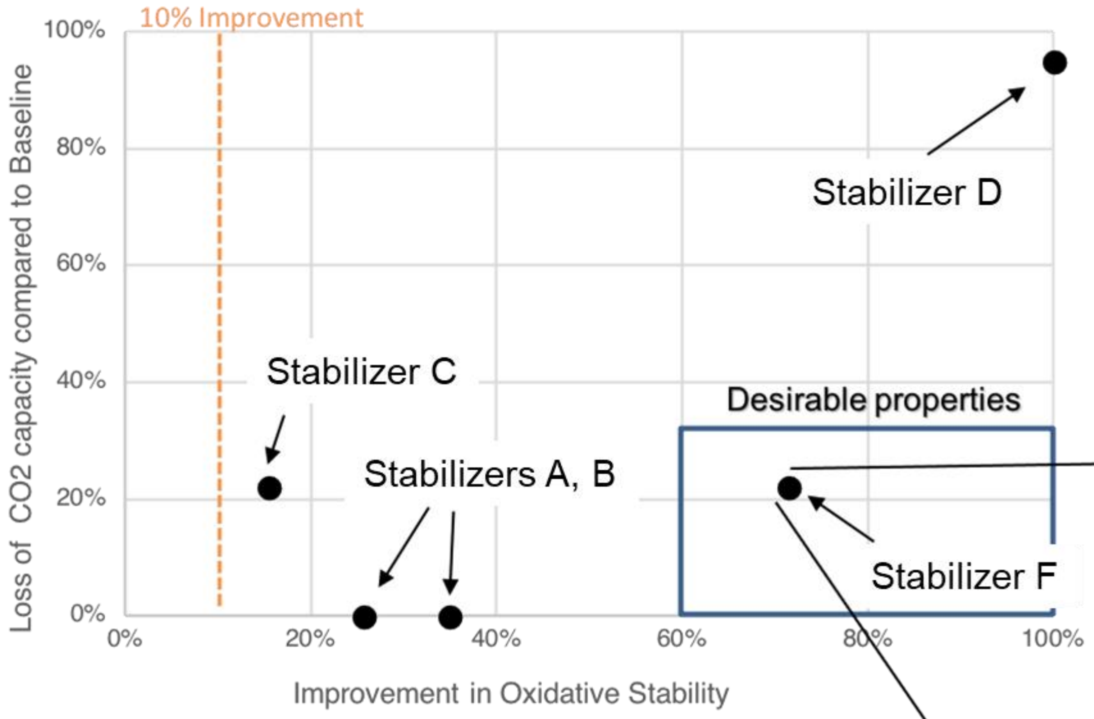
4 – Progress and Outcomes

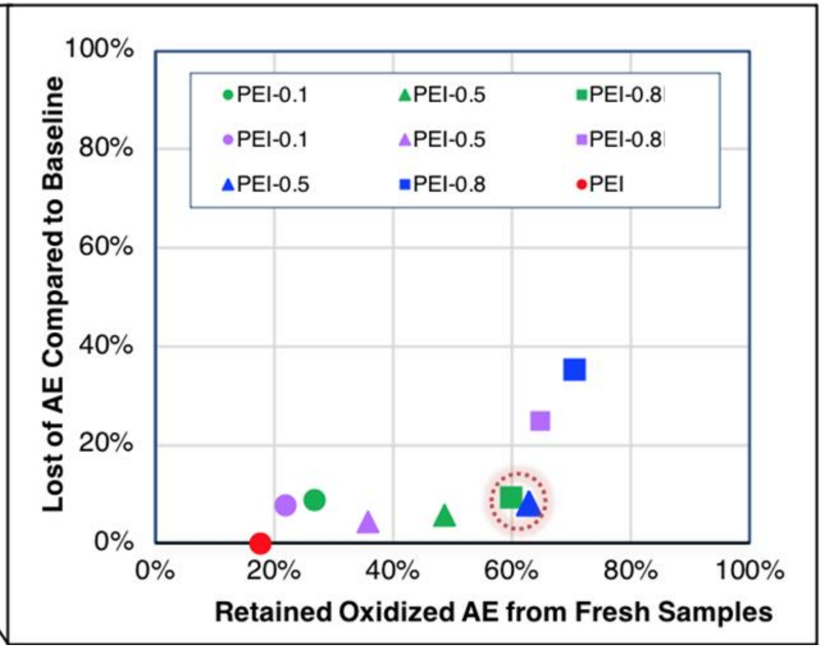
Mobile DAC system built, operates via computer control delivering 30 consecutive cycles at target production rate.





4 – Progress and Outcomes





Stabilizers that limit oxidative degradation of amine species, PEI, successful identified and demonstrated.

4 – Progress and Outcomes

Algenol PBR system successfully used to cultivate Arthrospira platensis (AB2293) outdoors for 16 days of continuous growth at end of summer 2020 season.

TEA

4 – Progress and Outcomes

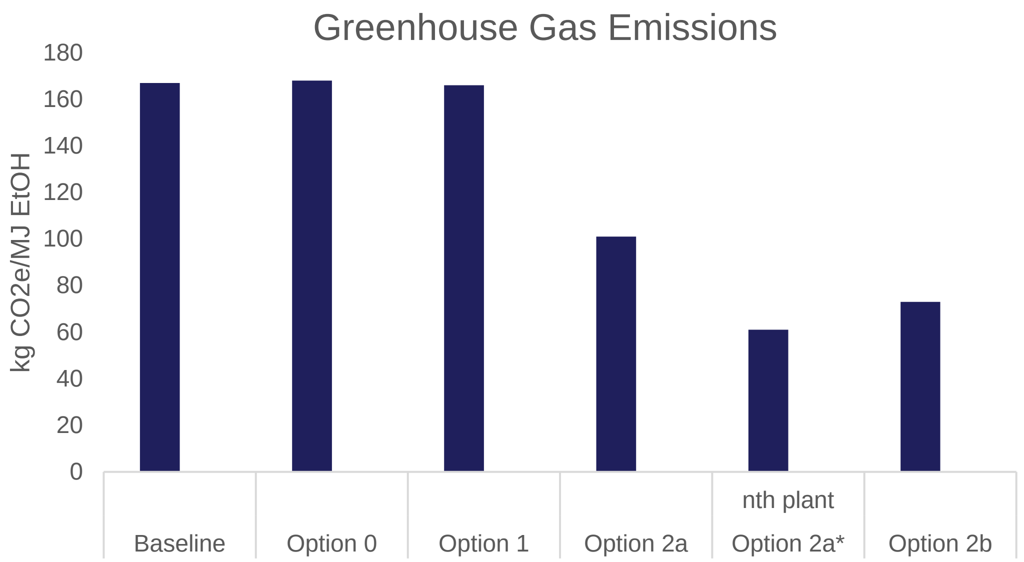
DAC Operating Hours	12	24	12	24	12	24	12	24	12	24	12	24
CO_2 Compressed/Stored	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes
Flue Gas CO_2 Utilized	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes

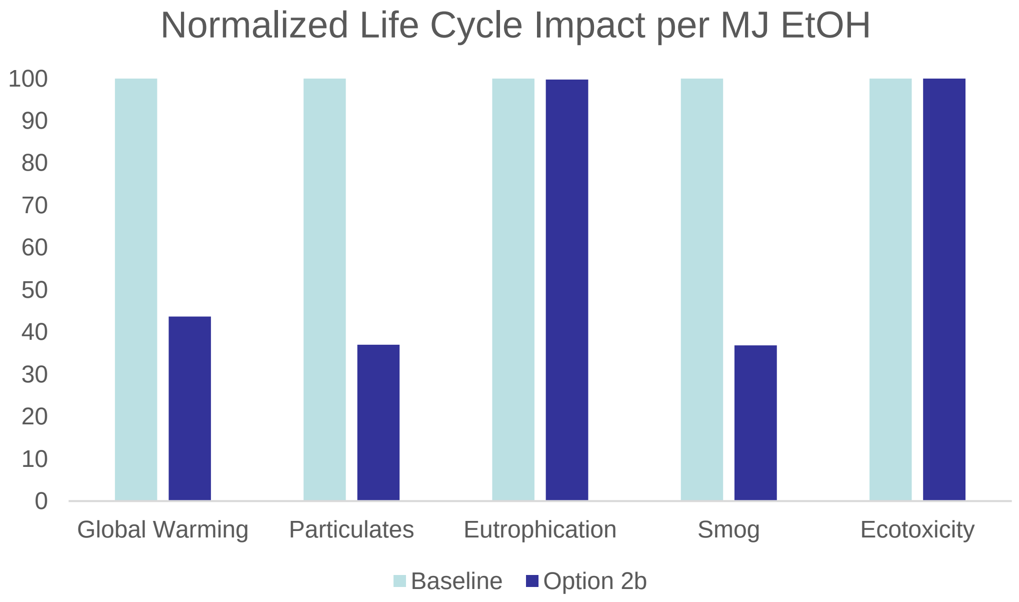
	Baseline	Option 0	Option 1	Option 2a	Option 2b	Option 2a – nth plant DAC
MFSP ($/gal EtOH)	$10.68	$9.33	$9.10	$8.78	$8.93	$8.25
%MFSP Reduction	-	12.6%	14.8%	**17.8%**	**16.4%**	**22.8%**
EtOH annual production (MMGal/yr)	16.0	16.0	16.0	16.0	16.0	16.0
FCI (MM$)	860.5	724.1	695.2	694.6	719.9	654.3
Total operating costs (MM$/yr)	53.6	51.5	51.8	47.2	45.7	44.8
CO_2 from DAC (tonne/hr)	40.0	20.0	17.9	12.9	18.9	14.9
DAC operating hours (hr/day)	12	24	24	24	12	24
Percent of total CO_2 demand from DAC	100%	100%	90%	64%	47%	75%

- **DAC-PBR integration Options 2a and 2b achieve and exceed the 15% cost reduction target**

LCA

4 – Progress and Outcomes





As shown in the figure on the left, Option 2b has 56% lower greenhouse gas emissions than the Baseline. The figure also shows emissions from the nth plant DAC design, which is more energy efficient and therefore previews lower emissions as the technology develops.

As shown in the figure on the right, with impacts normalized to 100%, the lifecycle impacts for particulate emissions and smog are lower for the integrated options (option 2b is shown), both because the use of natural gas is lower and because the flue gas emissions are significantly absorbed due to integration.

Summary

- Successful risk mitigation – added new co-PI and PBR set up at Georgia Tech after Algenol reduced their role to consulting partner
- Designed and built mobile DAC unit, demonstrated successful continuous operation for periods (12-15 hr) longer than a single growth period (10-12 hr)
- Developed oxidation resistant sorbents, which will improve both stand-alone DAC and DAC/PBR integration.
- 5 different DAC + PBR scenarios modeled. Two scenarios surpass Go/No-Go milestone of >15% MFSP Reduction.
- LCA anslyses of same scenarios demonstrate potential for reduced smog and particulates emissions, along with technology’s carbon footprint.
- Future work experimentally couples DAC and PBR, and experiments test TEA/LCA suggestions for improved integration options.

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05/03/2018

Additional Slides

1 – Management

BP2

Task	Description	Purpose
2	Design/Construct Mobile DAC System	Mobile unit for indoor DAC sorbent development & outdoor CO_2 capture & delivery to PBRs
3	*Baseline Performance of DAC Sorbents*	*Provide baseline DAC performance*
4	Initial TEA	DAC, PBR & combined DAC/PBR TEAs
5	*Initial LCA*	*DAC, PBR & combined DAC/PBR LCAs*
6	Commission & Test Mobile DAC System	Establish baseline operation with baseline DAC sorbents.
7	*Develop Oxidation-Resistant DAC Sorbents*	*Extend lifetime/stability of DAC sorbents*
8	PBR Set-Up & Commissioning	Demonstrate algae growth in PBRs (Arthrospira platensis AB2293)

Objectives:

1) Advance direct air capture (DAC) technology as a location agnostic CO_2 source.
2) Couple DAC with algae growth in PBRs to reduce siting constraints and/or the carbon footprint of algal biofuel production.

1 – Management

BP3

Task	Description	Purpose
8	Operate DAC System w/PBRs	Integrate DAC w/PBRs in outdoor algae cultivation
9	*Integrated TEA*	*Assess impact of DAC sorbent improvements and heat/mass streams with PBRs into TEA*
10	Integrated LCA	Assess impact of DAC sorbent improvements and heat/mass streams with PBRs into LCA
11	*Improved DAC Sorbents*	*Demonstrate performance of sorbents tailored for long-term stability*
12	Reconfigure DAC System based on Tasks 9-11	Combine experimental DAC sorbent improvements and TEA/LCA insights to improve DAC efficiency.
13	*Integrate Reconfigured DAC System with PBRs*	*Demonstrate revised DAC system with PBRs during outdoor algae cultivation*
14	Final TEA	Impact of program integration/optimization
15	*Final LCA*	*Impact of program integration/optimization*

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- *You may refer to them during the Q&A period if they are helpful to you in explaining certain points.*

Publications, Patents, Presentations, Awards, and Commercialization

- None

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