DOE Award Number DE-FE0032229

Algal Biorefinery Conversion of Utility CO_2 to High-Value Products (ABC-UC)

Colorado State University: Kenneth F. Reardon (Principal Investigator), Steve Conrad, Graham Peers, Jason Quinn

University of Wyoming: Maohong Fan

Living Ink Technologies: Fiona Davies

Wyoming Integrated Test Center: Will Morris

Project Kick-Off Meeting
June 23, 2023

Acknowledgement and Disclaimer

Acknowledgement
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Background

- There is a need to achieve net carbon-free electricity generation that is economically sustainable
  - One option is to use waste CO_2 to make valuable products
- Microalgae
  - Rapid growth relative to plants
  - Many species demonstrated to grow on flue gas
  - 100% of biomass is useable
  - Many conversion pathways demonstrated

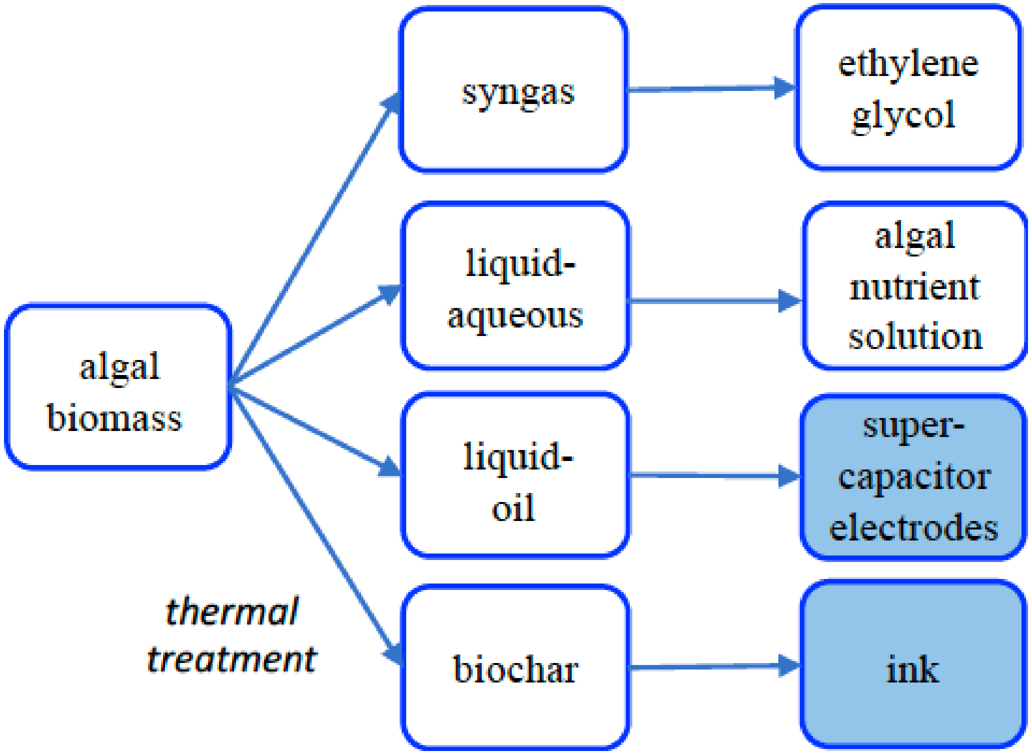
Project goals

- Demonstrate, characterize, and optimize a biorefinery process for converting a utility source of CO_2 to high value bioproducts via algal cultivation; and
- Demonstrate a carbon utilization efficiency greater than 50%, along with algal productivity greater than 20 g AFDW/$m^2 \cdot d$ in two 30-day campaigns.

Project objectives

- Develop/demonstrate efficient CO_2 transfer to algal cultivations;
- Develop strains and operations for algal cultivation from flue gas;
- Develop and optimize algal biomass conversion to products; and
- Conduct techno-economic analysis and life-cycle assessment.

Bioproducts



>$200/kg; $22.7 B global (2017)

$40/kg; $12.9 B global

Project team and prior work

- Colorado State University
  - Device for high-efficiency CO_2 transfer to algal ponds
  - Experience with many strains of microalgae and cyanobacteria
  - Characterization capabilities (photosynthesis, biomass, carbon)
  - Thermal conversion technologies
  - TEA and LCA (including water)

Project team and prior work

- University of Wyoming
  - Production of carbon nanofiber supercapacitor electrodes
  - Development of advanced separation technologies
- Living Ink Technologies
  - Expertise in pyrolysis
  - Expertise in production of algal inks
- Wyoming Integrated Test Center
  - Provides test space adjacent to coal plant

American Eagle uses Algae Ink on Apparel for a collaboration with the Surfrider Foundation

Patagonia Prints Hang Tags with Black Algae Ink

Marmot uses sustainable ink grown from algae with Mountain Works Crew collection.

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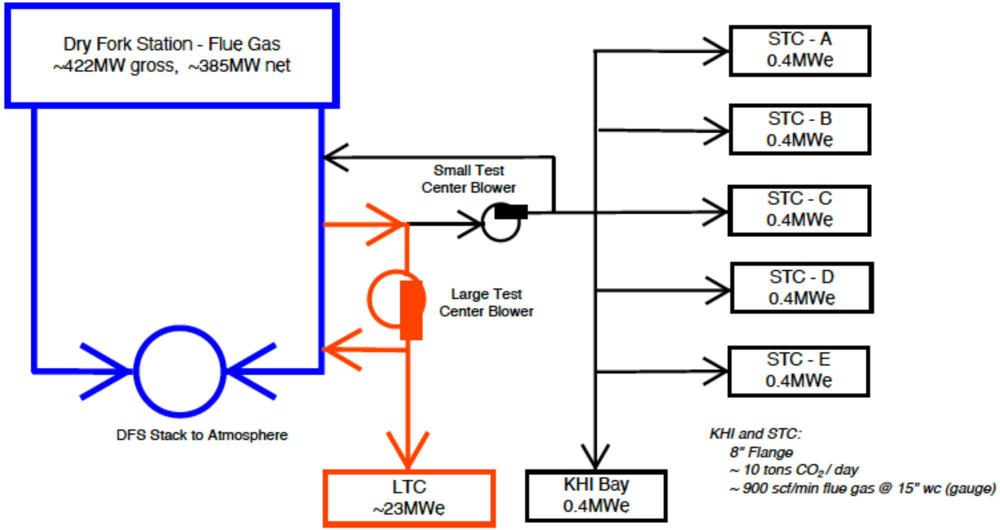
Wyoming Integrated Test Center



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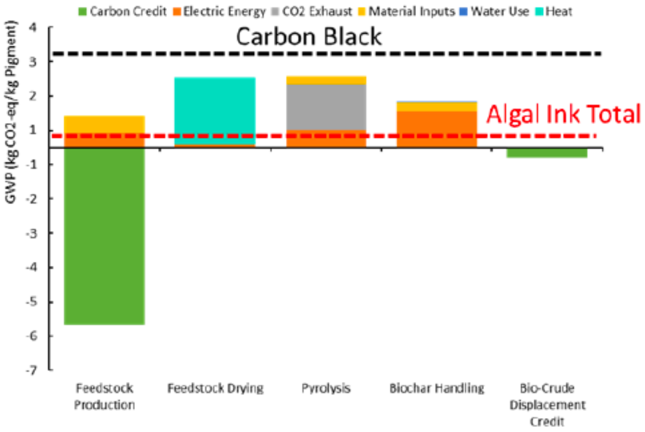
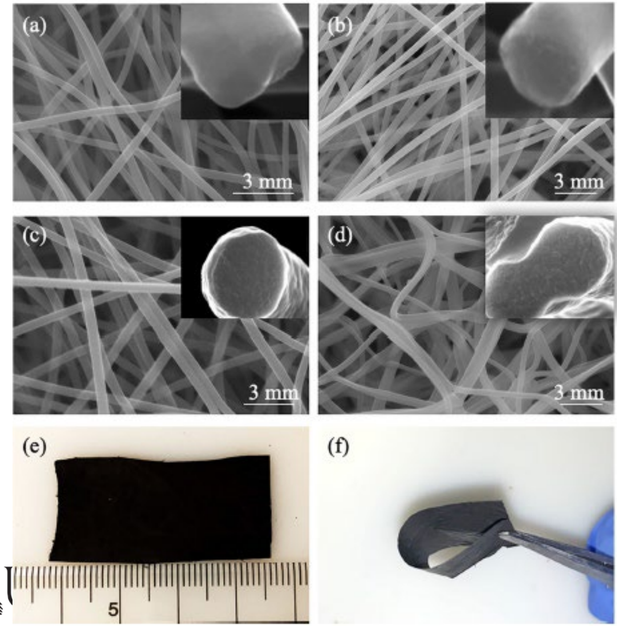
Project team and prior work

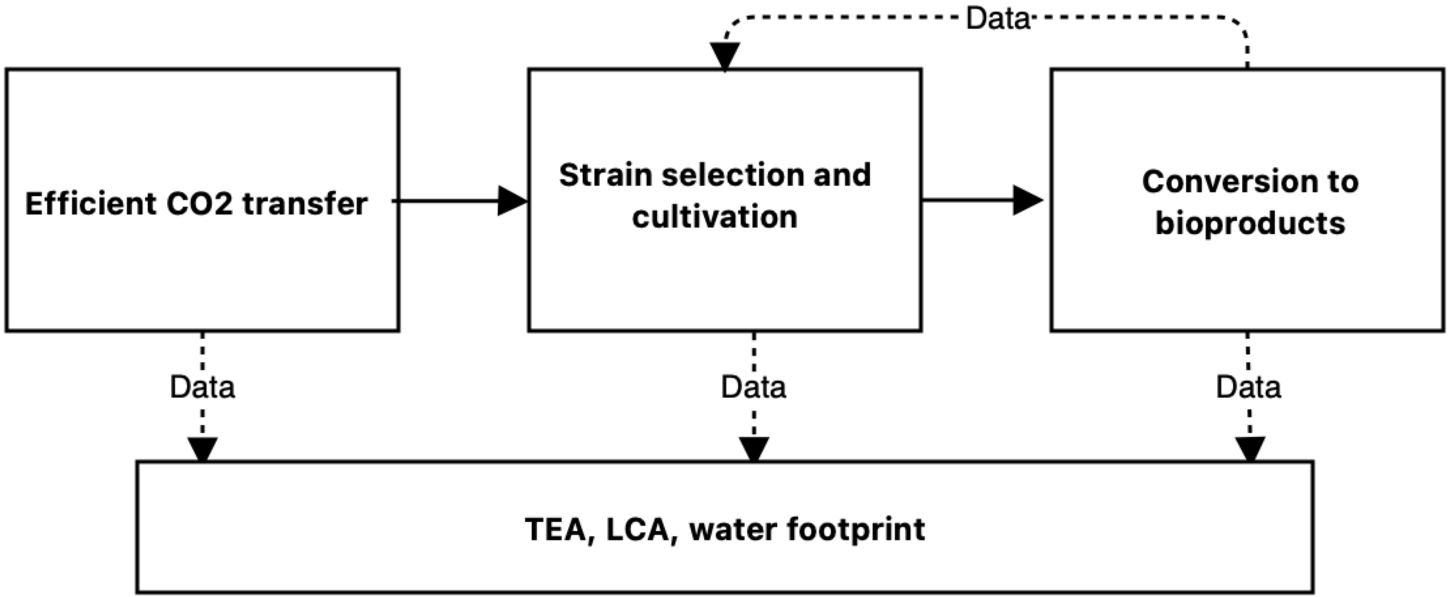
- Project team has worked together
  - CSU on prior and current DOE and NSF projects
  - CSU-Living Ink: LCA and TEA
  - CSU-Wyoming: carbon nanofiber materials



Fuel Processing Technology
Volume 225, January 2022, 107055

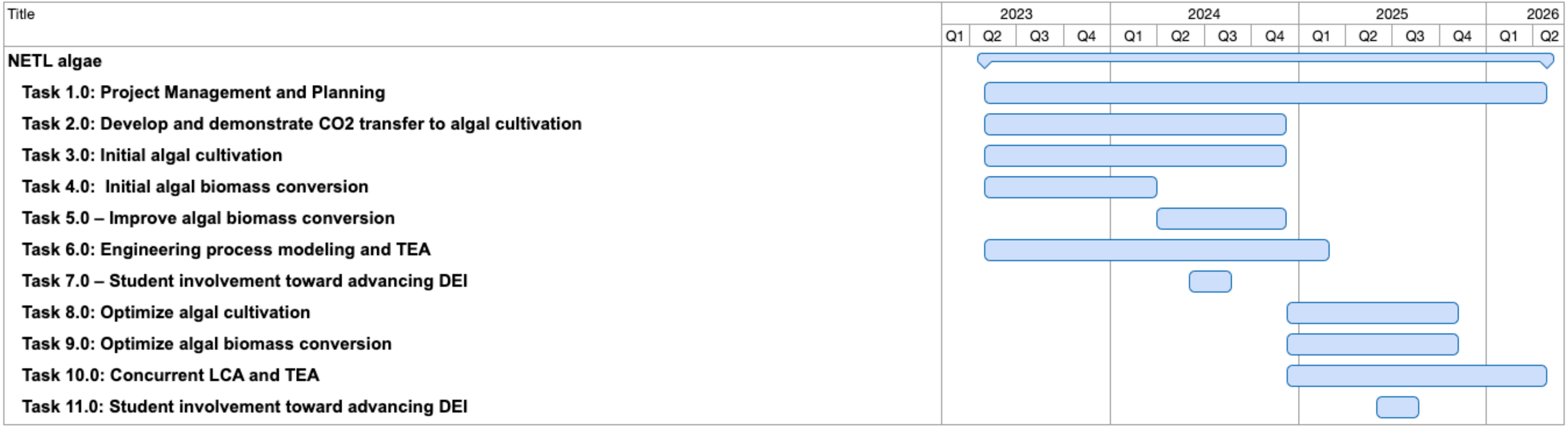


Project plan



Project timeline

Budget period 1: 5/1/2023 - 1/31/2025
Budget period 2: 2/1/2025 - 4/30/2026



Budget Period 1: Technology Development

- Task 1 – Project Management and Planning
- Task 2 – Develop and demonstrate CO_2 transfer to algal cultivation
- Task 3 – Initial algal cultivation
- Task 4 – Initial algal biomass conversion
- Task 5 – Improve algal biomass conversion
- Task 6 – Engineering process modeling and techno-economic assessment
- Task 7 – Student involvement toward advancing diversity, equity, and inclusion

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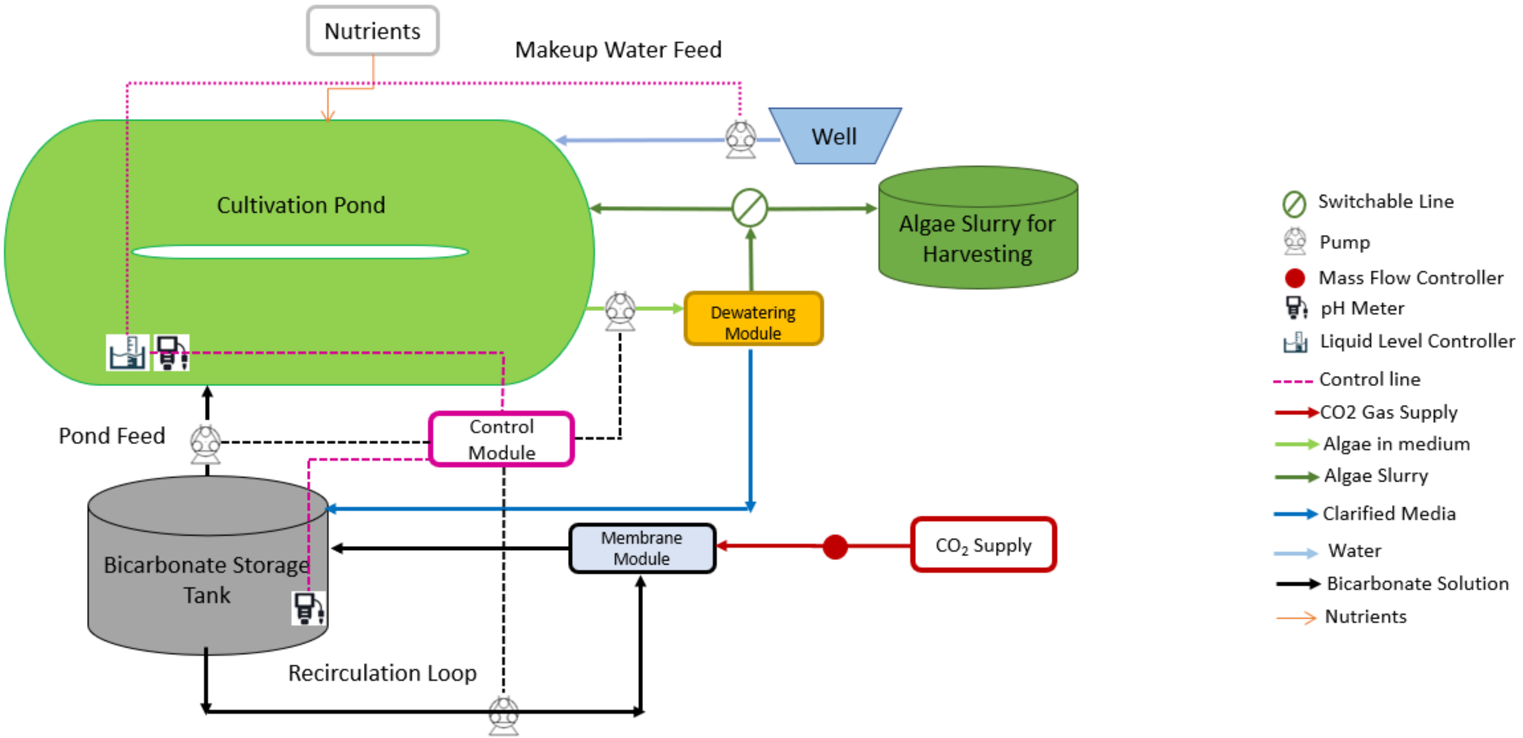
Task 2: Develop and demonstrate CO_2 transfer to algal cultivation

- 2.1 – Develop CO_2 transfer system with synthetic flue gas
- 2.2 – Evaluate performance of CO_2 transfer system with flue gas
- 2.3 – Optimize performance of CO_2 transfer system with flue gas

Task 2: Develop and demonstrate CO_2 transfer to algal cultivation



Task 3: Initial algal cultivation

- 3.1 – Cultivation of Tier 1 algal species
- 3.2 – Cultivation of Tier 2 algal species

Task 3: Tier 1 algal cultivation

Strain	*Phaeodactylum tricornutum*	*Nannochloropsis oceanica*	SAmud7 (no ID)	SRTC14 (no ID)	*Monoraphidium minutum*	*Picochlorum celeri*
Growth (final OD700)	-0.34	1.19	1.51	0.85	0.87	2.11

Conditions:
- ambient CO_2
- 18:6 light program at 320 mmol photons $m^{-2}s^{-1}$
- 20 and 35 °C

Next:
- Synthetic flue gas
- Scaling to 1 L
- More strains

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Task 4: Initial algal biomass conversion

- 4.1 – Initial thermochemical biomass conversion
- 4.2 – Development of thermal treatment liquid product separation method
- 4.3 – Evaluation of Tier 1 candidate biomass for ink
- 4.4 – Evaluation of Tier 1 candidate biomass for supercapacitor electrodes

Task 4.3 – Evaluation of Tier 1 candidate biomass for ink

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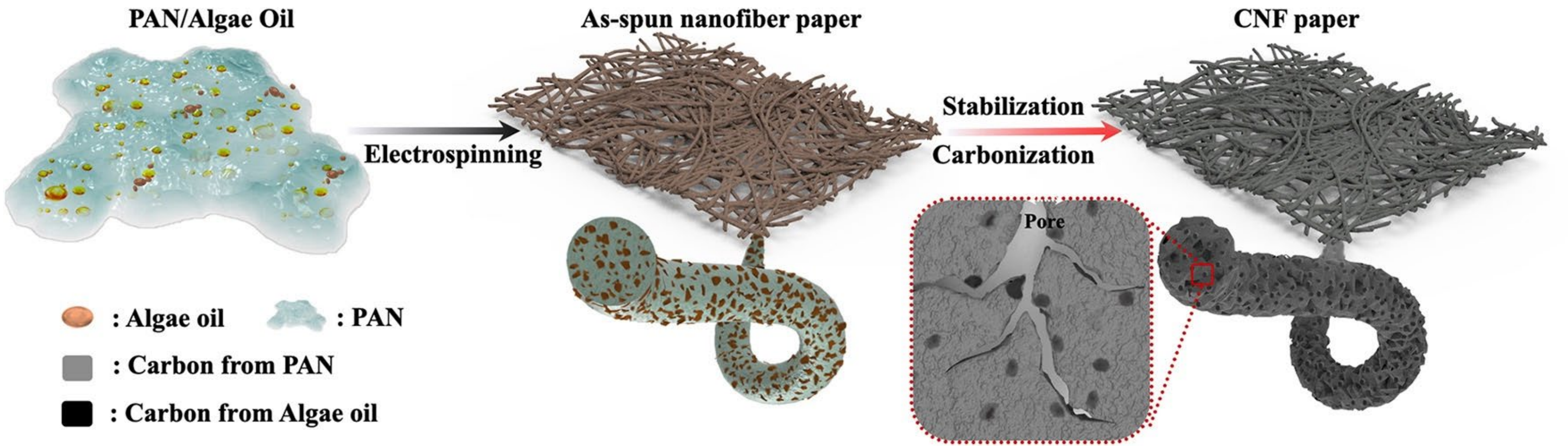
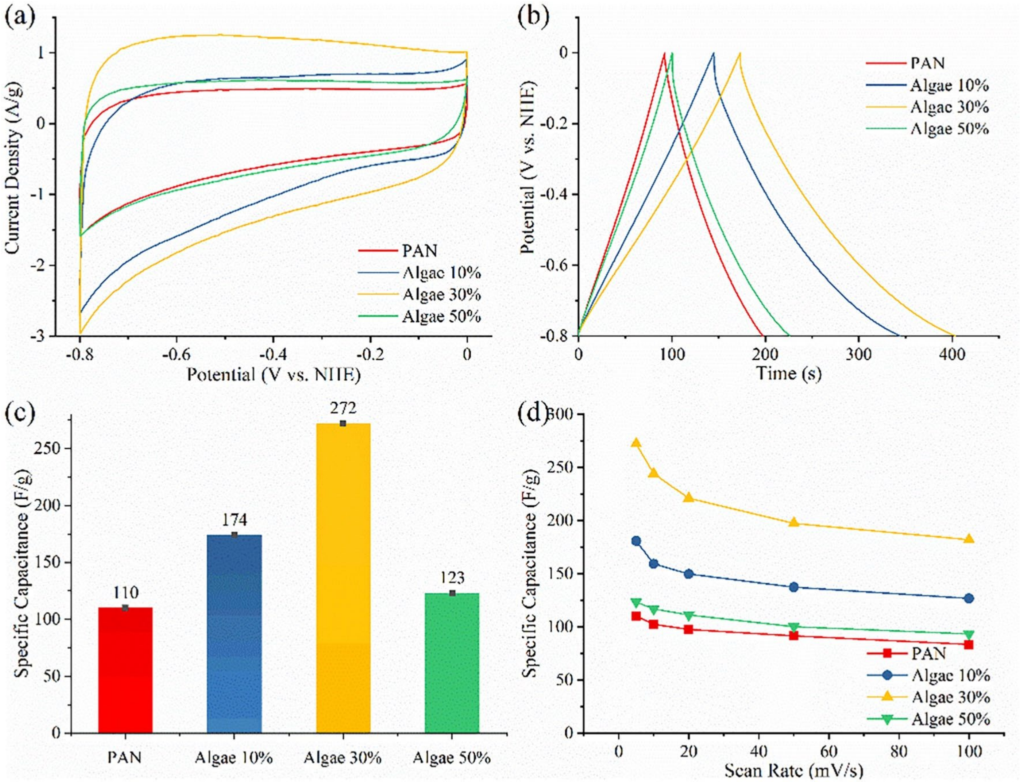
Task 4.4 – Evaluation of Tier 1 candidate biomass for supercapacitor electrodes



PAN: polyacrylonitrile

Task 4.4 – Evaluation of Tier 1 candidate biomass for supercapacitor electrodes



Wang, T.; He, X.; Gong, W.; Kou, Z.; Yao, Y.; Fulbright, S.; Reardon, K. F.; Fan, M., Fuel Processing Technology 2022, 225, 107055

PAN: polyacrylonitrile

Task 5: Improve algal biomass conversion

- 5.1 – Improve thermochemical biomass conversion
- 5.2 – Production of ink from Tier 2 species biomass
- 5.3 – Production of carbon nanofiber supercapacitor electrodes from Tier 2 species biomass

Task 6: Engineering process modeling and techno-economic assessment

- 6.1 – Engineering process modeling
- 6.2 – Techno-economic analysis
- 6.3 – Initial life-cycle assessment
- 6.4 – Initial water footprint

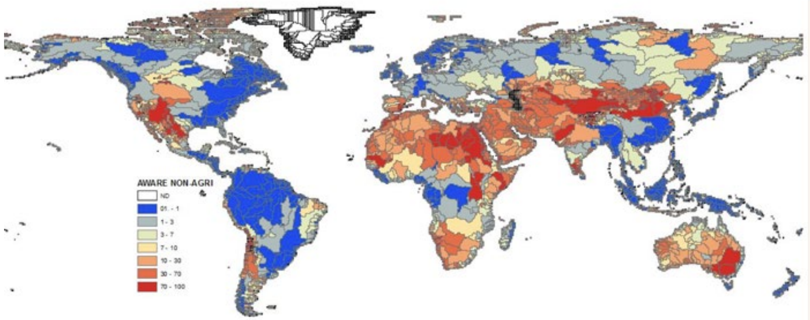
Task 6: Engineering process modeling and techno-economic assessment

Develop a dynamic LCA framework to explore the water footprint

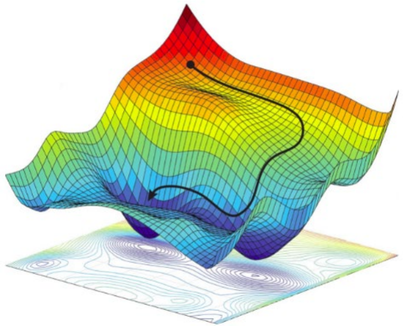
- Expand upon the **A**vailable **WA**ter **RE**maining (AWARE) water scarcity footprint framework
- Add a temporal component to water footprint metrics considering regional water scarcity

Conduct multi-objective optimization modeling

- TEA, LCA and water footprint analyses
- Optimize algal cultivation and conversion/processing strategies



AWARE Regional Characterization Factors
https://wulca-waterlca.org/aware/what-is-aware/



Task 7: Student involvement toward advancing diversity, equity, and inclusion

- 7.1 – Involve undergraduates from diverse backgrounds in research

BP 1 success criteria

- Demonstration of bubble-free CO_2 delivery system operation for a 1,000-L pond for 30 days using flue gas, consistently achieving 90% of inorganic carbon saturation in the system storage tank.
- Laboratory demonstration of two algal strains with superior biomass productivity that provide good quality biomass for ink and supercapacitor electrode production.
- Demonstrated production of ink pigment with acceptable color density, and texture.
- Demonstrated production of a supercapacitor material with specific capacitance of ≥300 F/g.
- Completion of water footprint framework for measuring efficiency and process decisions defined to inform environmental impact targets and source water requirements.

Budget Period 2: Deployment and Demonstration

- Task 1 – Project Management and Planning
- Task 8 – Optimize algal cultivation
- Task 9 – Optimize algal biomass conversion
- Task 10: Concurrent life cycle assessment and techno-economic modeling
- Task 11: Student involvement toward advancing diversity, equity, and inclusion

Summary

- Recent project start
- Production of two high-value products
- Capitalizing on prior DOE projects
- Strain selection, CO_2 transfer underway
- Innovative LCA approach considering water

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Budget overview

	DOE $	Cost Share $	Total $
BP 1	1,194,541	316,916	1,511,457
BP 2	805,374	231,083	1,036,457
Total	1,999,915	547,999	2,547,914

Cost share: 21.5%

Project timeline

- Budget period 1: 5/1/2023 - 1/31/2025
- Budget period 2: 2/1/2025 - 4/30/2026

Project tasks

Budget Period 1

- Task 1 – Project Management and Planning
- Task 2 – Develop and demonstrate CO_2 transfer to algal cultivation
- Task 3 – Initial algal cultivation
- Task 4 – Initial algal biomass conversion
- Task 5 – Improve algal biomass conversion
- Task 6 – Engineering process modeling and techno-economic assessment
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Budget Period 2

- Task 1 – Project Management and Planning
- Task 8 – Optimize algal cultivation
- Task 9 – Optimize algal biomass conversion
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Milestones

Subtask	Milestone Title & Description	Date
6.1	Completed energy and mass balances for the baseline pathway and 2 alternative pathways.	M 3
3.1	All Tier 1 algae strains scaled to 1-L cultivation for productivity assays.	M 6
2.1	Demonstration of bubble-free CO_2 delivery system operation for 30 days using synthetic flue gas.	M 9
4.1	Demonstration of HTL product formation from three independent conversion processes.	M 9
6.2	Initial technoeconomic analysis completed.	M 12
7.1	In the second project year, at least three undergraduate students will be involved in the project, at least two of whom are from underserved communities or underrepresented groups.	M 15
6.3	Greenhouse gas results with performance targets defined to meet environmental impact targets.	M 18
5.2	Technical evaluation of six independent Tier 2 pigment samples from HTL and pyrolysis conversion will be performed.	M 21
10.1	Development and validation of algal growth model.	M 24
10.2	Evaluation and comparison of several production pathways based on the metrics of greenhouse gas accounting and minimum selling price.	M 27
11.1	In the third project year, at least three undergraduate students will be involved in the project, at least two of whom are from underserved communities or underrepresented groups.	M 27
8.1	Screen 10 evolved strains for improved biomass productivity.	M 30
9.3	The specific capacitance of the CNSC material remains at ≥94% of its initial value after 10,000 cycles of charge-discharge tests.	M 30
10.4	Specific determination of water use and return on water invested for several production flows and reuse points.	M 33
10.3	Certainty of greenhouse gas results determined through stochastic modeling that is informed through experimental data.	M 36

Team member roles

KF Reardon (CSU), PI, Tasks 1, 2, 7, 11

Project management; CO_2 delivery; algal cultivation; students

- **G Peers (CSU), Tasks 3 and 8**: algal cultivation
- **F Davies (LI), Tasks 4, 5, and 9**: biomass conversion; ink pigment production
- **M Fan (UW), Tasks 4, 5, and 9**: liquid separation; carbon supercapacitor electrode production
- **JC Quinn (CSU), Tasks 4, 5, 6, 9, and 10**: biomass conversion; LCA and TEA
- **S Conrad (CSU), Tasks 6 and 10**: LCA (water footprint)

Project technical risks

Perceived Risk	Risk Rating			Mitigation/Response Strategy
	Probability	Impact	Overall	
Task 3: All chosen algal strains are sensitive to high CO_2 found in flue gas	Low	Med	Med	Some species chosen for Tier 1 have been grown with flue gas. If problems, we will acquire alternate species.
Task 4: Biochar and bio-oil derived from specific algae strains will not be compatible with products.	Low	Low	Low	*Arthrospira platensis* is included as a test species list because Living Ink has successfully commercialized ink using this strain as a viable biomass source. Wyoming has used this oil to make electrodes.
Task 8: Tier 2 algal strains show poor biomass productivity on flue gas	Low	Low	Low	The 2 best strains from Tier 1 will be immediately assayed for growth on flue gas. If there is growth inhibition, alternates will be used.
Task 9: Impurities and chemical residues from growth media/flue gas will negatively affect the biochar and bio-oil quality.	Low	Med	Low	If modulating the nutrient load from growth media and flue gases is not successful, Living Ink has developed proprietary processing steps to reduce chemical impurities in biochar. These techniques can alter the ash content, particle size, porosity, and surface chemistry of biochar to improve color and texture characteristics.

Task 1: Project Management and Planning

- 1.1 – Project Management Plan
- 1.2 – Performance Data Table
- 1.3 – Environmental Justice Questionnaire

Task 8: Optimize algal cultivation

- 8.1 – Adaptive evolution of Tier 2 algal species
- 8.2 – Optimize cultivation of Tier 2 algal species

Task 9: Optimize algal biomass conversion

- 9.1 – Optimize thermochemical biomass conversion
- 9.2 – Optimize and scale production of ink
- 9.3 – Optimize production of CNSC electrodes

Task 10: Concurrent life cycle assessment and techno-economic modeling

- 10.1 – Dynamic growth modeling
- 10.2 – Sensitivity, scenario, and optimization
- 10.3 – Updated techno-economic and life-cycle assessment
- 10.4 – Water footprint

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Task 11: Student involvement toward advancing diversity, equity, and inclusion

- 11.1 – Involve undergraduates from diverse backgrounds in research

BP 2 success criteria

- Demonstration of >50% CUE and algal productivity >20 g AFDW/m^2·d. Both metrics will be established over the course of at least two cultivations of at least 30 days in 1,000-L algal ponds fed flue gas without negatively affecting biomass productivity or nitrogen utilization efficiency;
- Demonstration of at least two ink pigment samples with acceptable commercial characteristics will be demonstrated;
- Demonstration of at least one commercially viable supercapacitor electrode material with specific capacitance that remains at ≥94% of its initial value after 10,000 cycles of charge-discharge tests; and
- Complete environmental and economic sustainability analyses for the biorefinery that characterize the desirability of the processes.