Life Cycle Analysis of Advanced Algal Systems

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Systems Assessment Center
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WBS #1.3.5.204

2023 BETO Peer Review
April 4, 2023

Project Overview

Guiding development of sustainable algal biofuels and bioproducts

Goal	**Evaluate the potential for sustainable scale up of algae production systems, algal biofuels, and algal bioproducts.**	• Inform decisions with detailed LCA and strategic case studies • Provide LCA results and datasets for key algae production and conversion pathways • Benchmark the state of technologies • Evaluate alternatives and advancements

Impact	**BETO and stakeholders can incorporate greenhouse gas and sustainability considerations in commercialization and R&D decisions.**	• Rigorous and detailed LCA addressing critical issues
		  o saline algae systems
		  o diverse CO_2 sources
		  o algal bioproducts
		  o integration with wastewater/manure management
		• Harmonization amongst BETO and FECM analysis efforts
		• Provide LCA tool to bioeconomy and LCA community

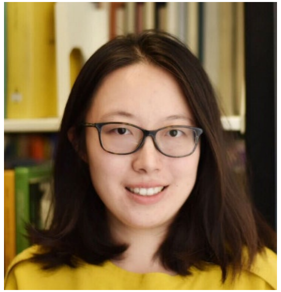
Relevance	**Addresses BETO goals for increasing the supply of sustainable algae and reducing the resource intensity of production, including system integration and resource recycling. Sustainable algae supports SAF goals.**	• Consistent, transparent LCA results • Benchmarked against other analyses/studies • Rigorous, reliable, and timely responses to key questions from BETO and its stakeholders • Peer-reviewed publications and models

Image source: https://pixabay.com/illustrations/compass-north-south-east-west-2925824/

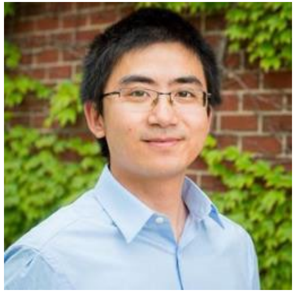
Approach

Project Team with diverse backgrounds to address varied aspects of algal systems

Troy Hawkins
Project Lead



Jingyi Zhang
Energy Systems Analyst



Hao Cai
SCSA Lead

Longwen Ou
Energy Systems Analyst

Ulises Gracida
Energy Systems Analyst

Udayan Singh
Post-Doctoral Researcher

Sudhanya Banerjee
Post-Doctoral Researcher
(2019-2022)

Approach

Tasks aligned with BETO's goals

And focused on key questions for understanding life cycle metrics for algal systems

1. LCA of saline algae production systems	Provide life cycle energy and environmental results for saline strain algae production and to compare with freshwater algae production systems. Adding detailed analysis of saline pond operations, brine management, and interactions between salinity and conversion.
2. Impacts of CO_2 sources on algae-based system	Evaluate the life cycle energy and environmental implications of options for CO_2 sources for algae production, including coal and natural gas combustion; high-purity sources such as steam methane reforming, biogas, and fermentation; and direct air capture.
3. LCA of algae-based bioproduct pathways	Understand the benefits and tradeoffs of pathways for producing valuable products from algae through comparison with conventional pathways. High-value products such as polyurethane improve algae economics. Bulk products, e.g. animal feed, make use of algal protein.
4. Integration of algae cultivation with wastewater and manure management	Understand the life cycle energy and environmental effects of integrating algae production with wastewater treatment (WWT) and manure management systems.
5. Harmonization of Algal Systems TEA, LCA, & Resource Assessment	Coordinate and harmonize technoeconomic analysis, LCA, and resource assessment activities within BETO's Advanced Algal Systems program.

Interacting with other relevant project teams to harmonize and leverage efforts

Algal Biomass Production R&D

GLOBAL ALGAE

Conversion R&D

CO_2 Utilization

GLOBAL CO_2 INITIATIVE
UNIVERSITY OF MICHIGAN

NATIONAL ENERGY TECHNOLOGY LABORATORY

LCA of Advanced Algal Systems

GREET
LIFE-CYCLE MODEL

Other DOE Algae Project Teams

HY-TEK Bio

UNIVERSITY OF MARYLAND

Washington University in St. Louis

Algal Biomass Availability Assessment

Pacific Northwest NATIONAL LABORATORY

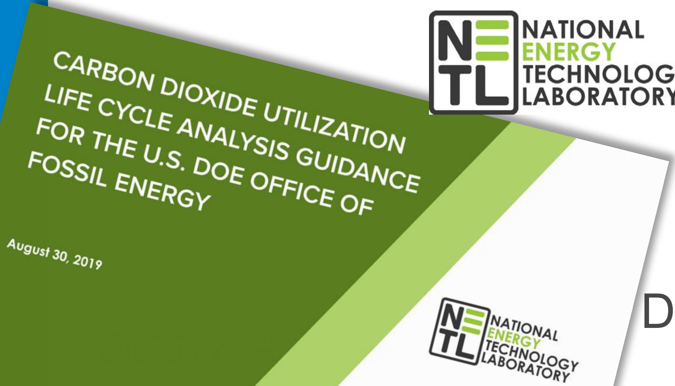
Conversion Process Modeling & TEA

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Algae Farm Cost Modeling

State of Technology and Design Case Benchmarking

Idaho National Laboratory


CARBON DIOXIDE UTILIZATION LIFE CYCLE ANALYSIS GUIDANCE FOR THE U.S. DOE OFFICE OF FOSSIL ENERGY

August 30, 2019

NATIONAL ENERGY TECHNOLOGY LABORATORY

Approach Management plan & implementation strategy

1. **Milestones track progress**
   - Driving critical analysis
2. **Peer-reviewed publications**
   - Disseminate key results and document data
3. **Annual GREET releases**
   - Transparent, publicly-available models and data, distributed broadly
   - Results incorporated in pathways for heavy duty vehicles, marine sector, bioproducts
4. **Regular communication**
   - Mitigates risk associated with data handoffs to/from other project teams

Quarter	*Milestone Title*		*Date*
Quarterly FY21Q1	Scope, data, and method for comparison of CO_2 sources for algae production including direct air capture	✓	12/31/20
Quarterly FY21Q2	Results for LCA of saline strain algae production	✓	3/31/21
Quarterly FY21Q3	Draft results for algae cultivation with CO_2 from direct air capture	✓	6/30/21
Annual FY21Q4	Report on comparison of CO_2 sources for algae production	✓	9/30/21
Annual FY22Q4	LCA of algae bioproduct pathways.	✓	9/30/22
Annual FY22Q4	LCA of integration of algae cultivation with wastewater and manure treatment systems		9/30/23

Challenges, Risks, and Mitigation Strategies

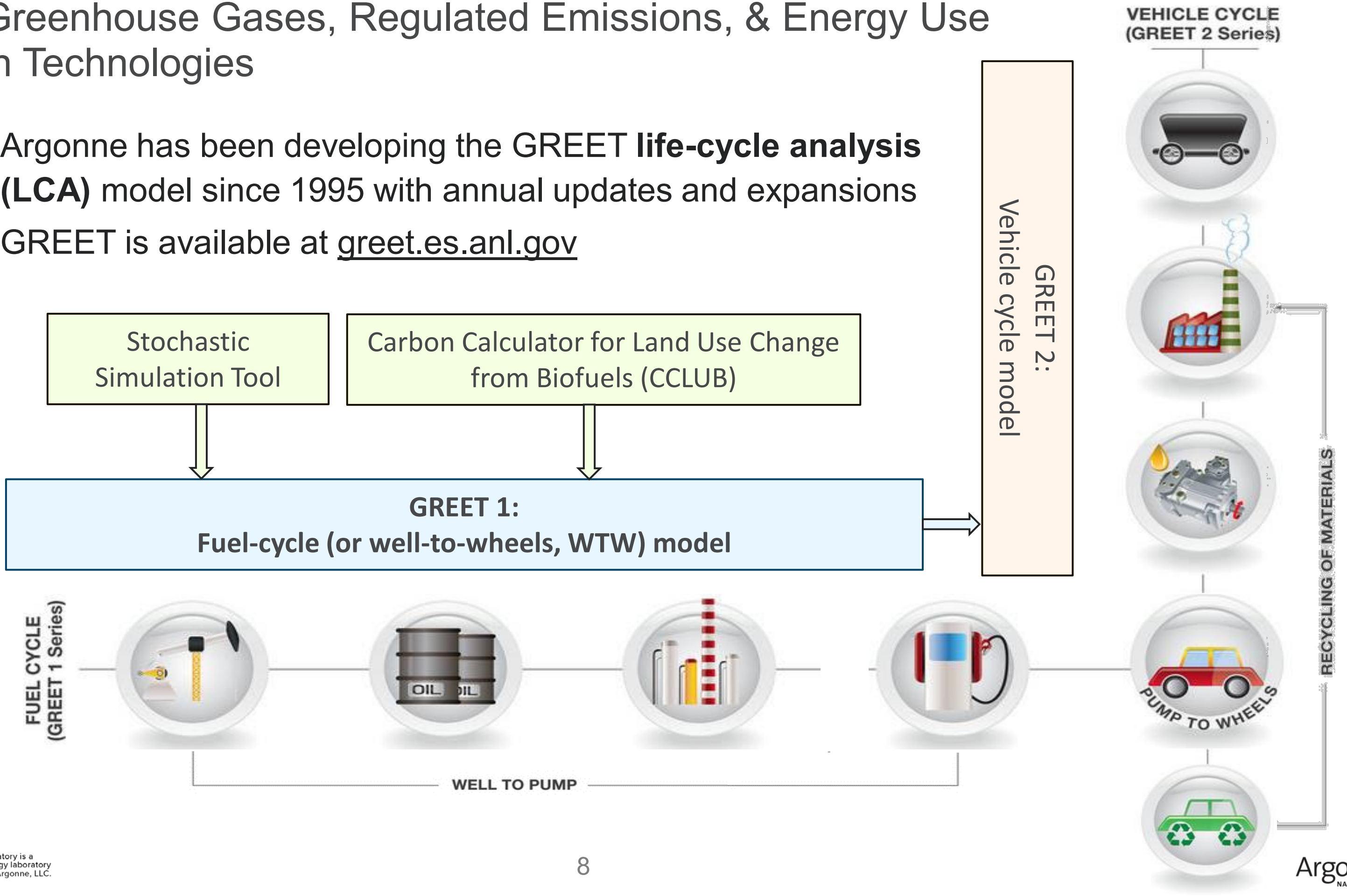
Challenges and Risks	Risk Mitigation Strategy
Data/information gaps affect the credibility of LCA results	**LCA** leverages partners' data, models, and expertise incl. NREL and PNNL process modeling, PNNL Algae BAT, and data from RD&D projects, e.g. DISCOVR.
Delays in data handoffs between project teams and/or numerous iterations affect schedule and deliverable quality	**LCA team** communicates regularly to coordinate handoffs between Algae BAT (PNNL), Algae Farm Model (NREL), conversion process modeling (NREL & PNNL), and LCA. LCA framework automated to facilitate rapid updating.
Analysis becomes disconnected from evolving industry directions	**LCA team** strategically engages with partners incl. through non-disclosure agreements, parallel projects, and industry conferences, e.g. Global Algae, Hytek Bio, U Maryland, WUSL, & ABO.

Approach

GREET Model Framework

Greenhouse Gases, Regulated Emissions, & Energy Use in Technologies

- Argonne has been developing the GREET **life-cycle analysis (LCA)** model since 1995 with annual updates and expansions
- GREET is available at greet.es.anl.gov



Approach

Biofuels in GREET can be connected with the full range of end use sectors

Share of US transportation GHG emissions; remaining 12% for US is from pipelines and offroad.

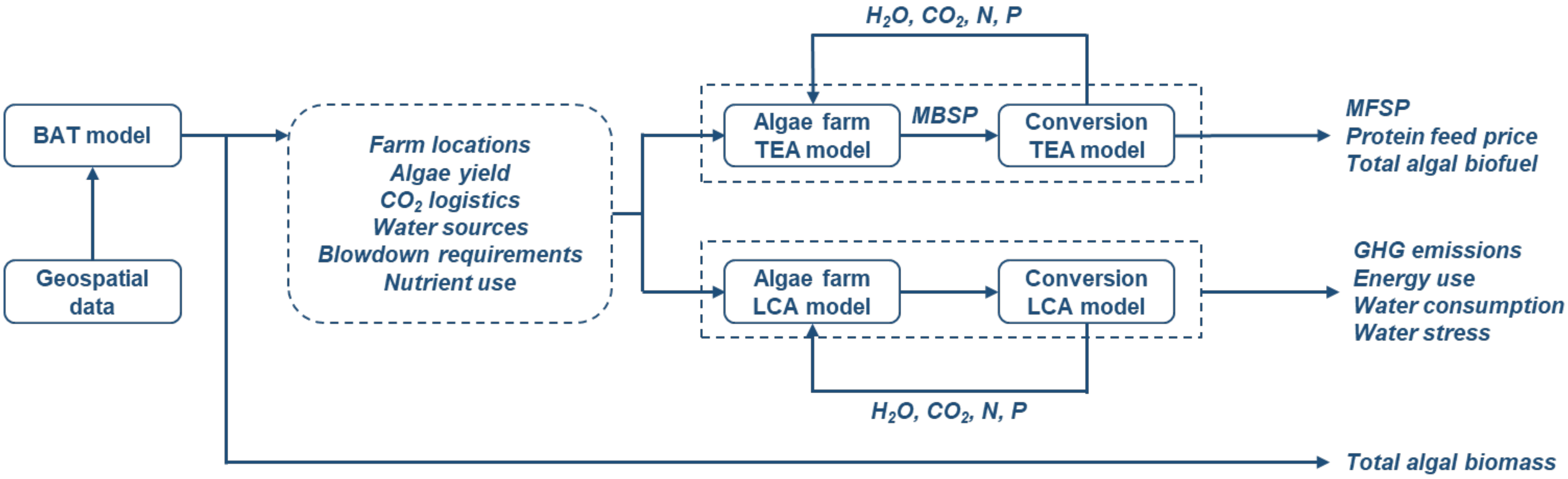
Approach

Metrics for GREET Microalgae Life Cycle Analysis

Greenhouse Gases	Water Consumption	Criteria Air Pollutants	Energy Use
Carbon dioxide Methane Nitrous Oxide Black carbon Albedo Characterized by global warming potential (CO_2-eq.) based on IPCC AR5.	Withdrawals less local releases AWARE US model estimates regional and seasonal water stress (With EJ implications)	Volatile Organic Compounds (VOCs) Carbon Monoxide (CO) Nitrogen Oxides (NO_x) Particulates ($PM_{2.5}$, PM_{10}) Sulfur Oxides (SO_x) Distinguished as Urban and Non-Urban (with EJ implications)	Total energy incl. fossil and renewable • petroleum • natural gas • coal • biomass • nuclear • hydro • wind • solar

Approach

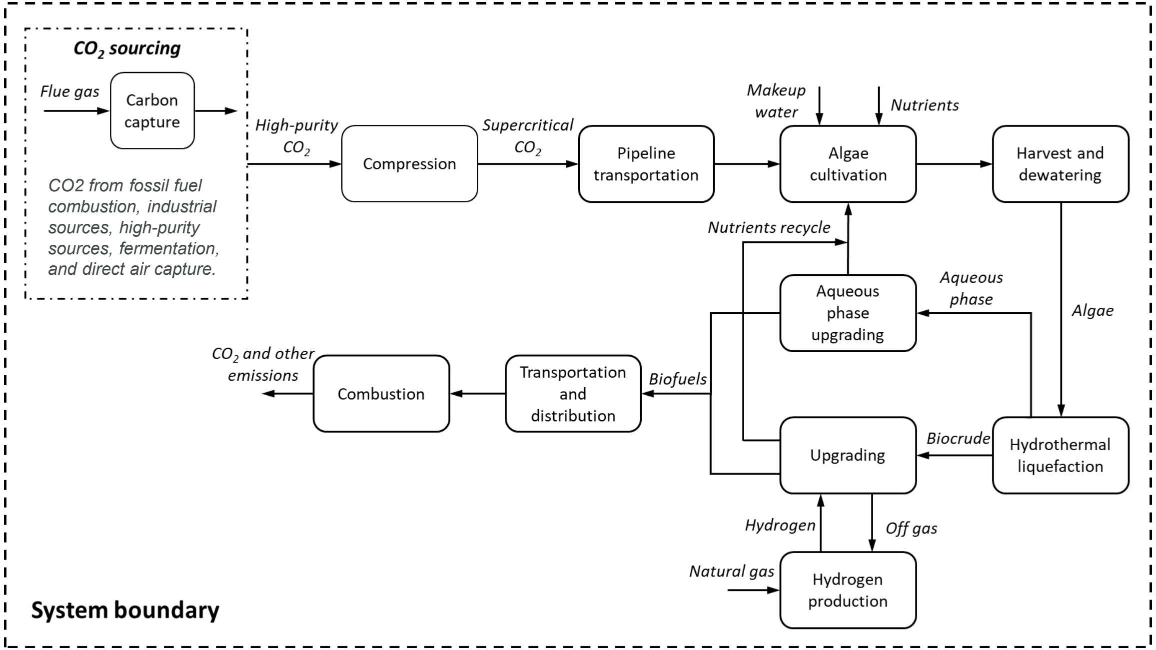
Harmonization Analysis Data Flows Across Models



Close collaboration across PNNL Algae Biomass Availability Tool, NREL Algae Farm Model, NREL & PNNL Aspen conversion process models, and Argonne GREET modeling

Harmonized LCA across full range of CO_2 sources for algae cultivation

- Harmonized modeling of current and future CO_2 capture and compression
  - Integrated Environmental Control Model (CMU).
  - NETL TEAs
  - GREET CO2U models
- Address multiple allocation/system expansion approaches
  - Cutoff approach
  - NETL CO2U Guidance (system expansion)
  - Shared benefit/allocation
- Results build consensus
  - Importance of distinguishing biogenic and fossil CO_2 sources
  - Implications of allocation/system expansion approaches.



Approach

AWARE US for Water Stress Impact Analysis

- Impact of water consumption varies by location
  - Depending on regional supply (runoff) and demand (ecosystems and existing societal demand)
- AWARE-US characterizes water stress by county
  - CF<1: water abundant
  - CF>1: water stress (compared to US average)

Water scarcity footprint (WSF) (m^3 *eq.*)

$$= [\text{Water consumption}]_i\ (m^3) \times [\text{AWARE CF}]_i$$

CF: characterization factor

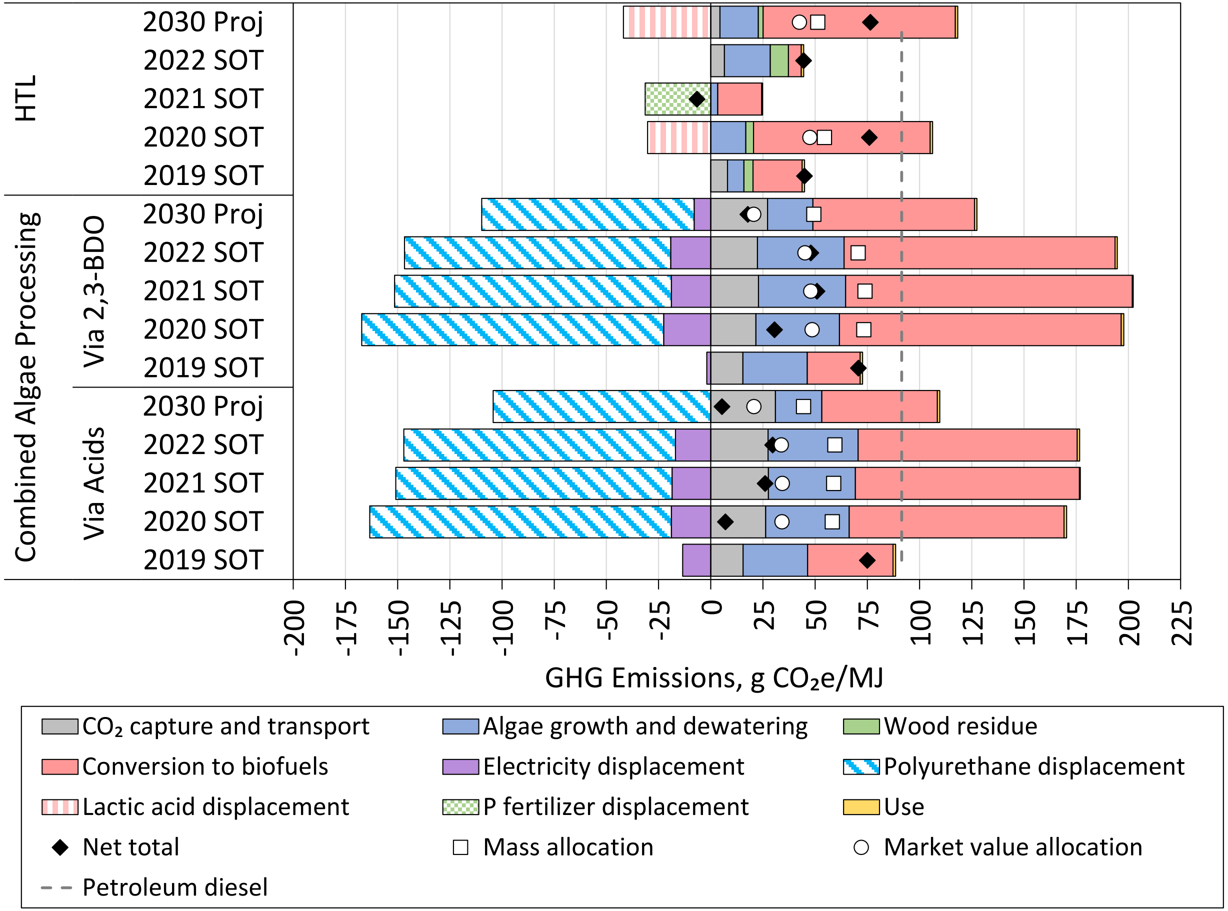
Lee et al. (2019) *AWARE-US: Quantifying Water Stress Impacts of Energy Systems in the United States*
Xu et al. (2019) *Assessment of Algal Biofuel Resource Potential in the United States with Consideration of Regional Water Stress*
Xu et al. (2020) *Balancing Water Sustainability and Productivity Objectives in Microalgae Cultivation: Siting Open Ponds by Considering Seasonal Water-Stress Impact Using AWARE-US*

Progress & Outcomes

Supply chain sustainability analyses identify opportunities for improving algal biofuel sustainability

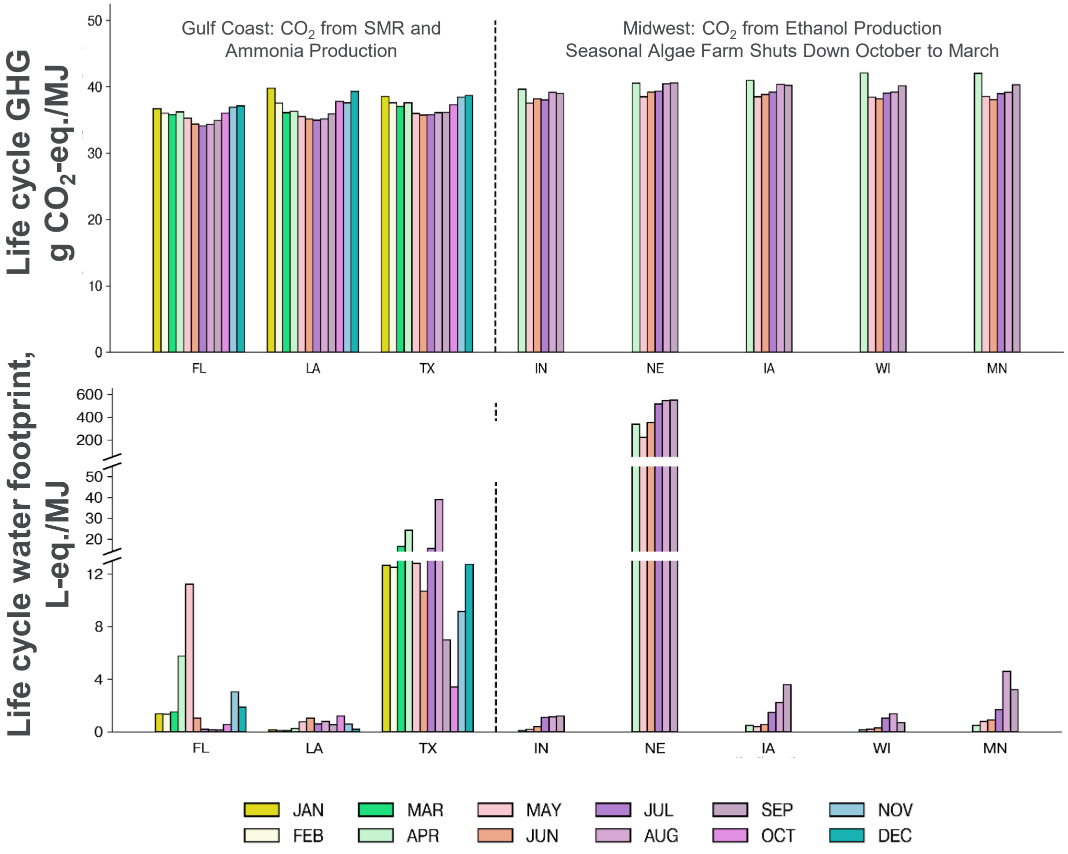
- Displacement credits for co-products significantly affect results, particularly for polyurethane.
- Improvements in algal productivity reduce life cycle GHGs in 2030.
- New analysis provides perspectives for subprocess mass- and market-based allocation, in addition to system expansion results.

(Cai et al., 2022)



Progress & Outcomes

High-purity CO_2 from Midwest ethanol production could enable seasonal algae farming



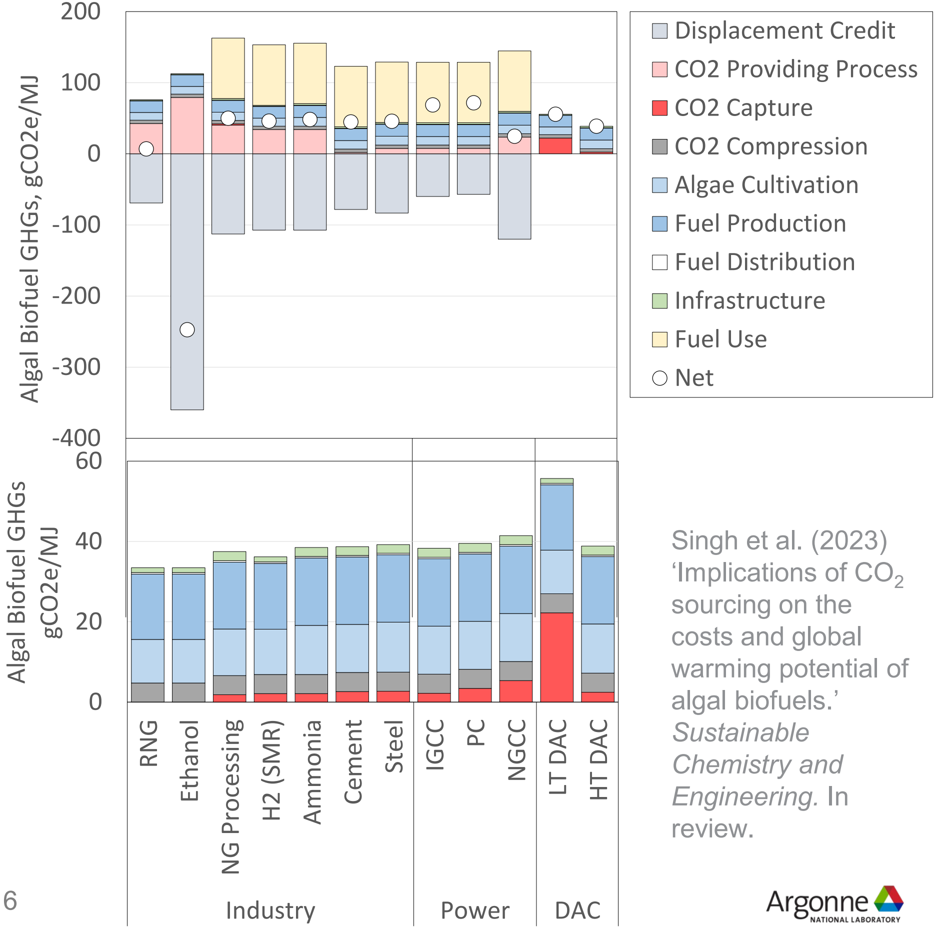
Ou et al. 2021

- GHGs for Midwest comparable to southern sites April-September.
- Sites with high-purity CO_2 perform better than favorable conditions in Florida with combustion CO_2 source.
- High-purity CO_2 from ethanol production in Midwest and from ammonia and steam methane reforming in Texas and Louisiana.
- Some Midwest sites have favorable water availability compared with Texas and Florida.
  - Nebraska illustrates importance of water stress screening.

Progress & Outcomes

Building consensus around the GHG impact of using fossil, biogenic, or direct capture CO_2 for algae farming

- The CO_2 source used for algae production affects GHG emissions and the contribution of algal biofuels to decarbonization.
- System expansion (top) considers the CO_2 providing process and distinguishes atmospheric/biogenic & fossil CO_2 sources.
  - Lower GHG results for atmospheric CO_2.
  - Higher GHG results for fossil CO_2.
  - DAC promising for future.
- The 'cut off' approach (bottom) illustrates effect of purity of CO_2 sources on life cycle GHG emissions.
- Results helping bridge a "gap" between past BETO algae LCA and NETL CO_2U LCA Guidance.



Singh et al. (2023) 'Implications of CO_2 sourcing on the costs and global warming potential of algal biofuels.' *Sustainable Chemistry and Engineering*. In review.

Progress & Outcomes

BETO Algae Analysis Harmonization Report

Tradeoffs for Saline Algae

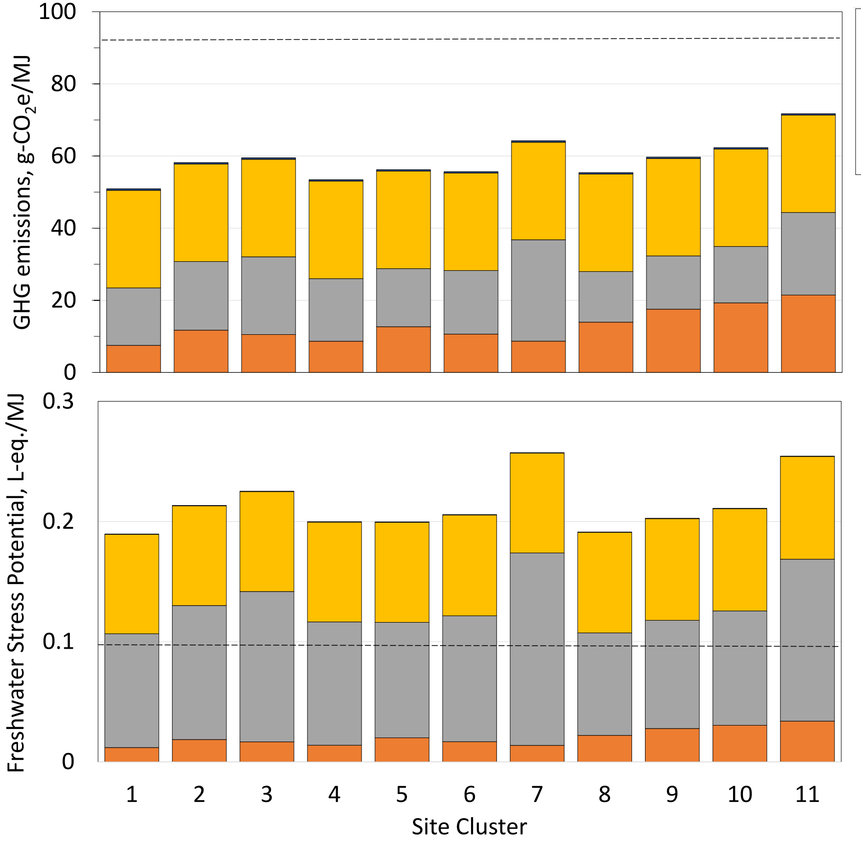
Saline algae cultivation avoids freshwater stress with tradeoffs for energy use and GHG emissions.

Benefits of Biogenic CO_2 and Direct Air Capture

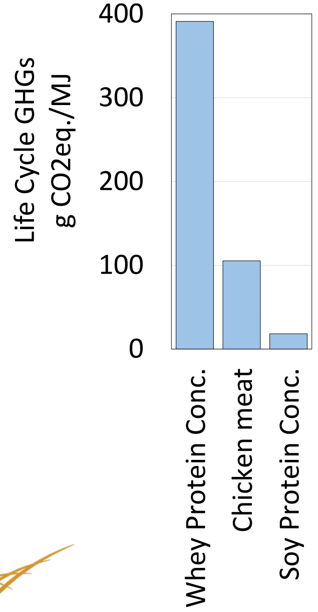
Algal cultivation using biogenic and direct air capture CO_2 sources is consistent with long-term decarbonization goals.

Challenges for biofuels from high-protein algae

LCA results highly dependent on coproduct or allocation assumption.



Algal protein conc. net credit for displacing alternatives



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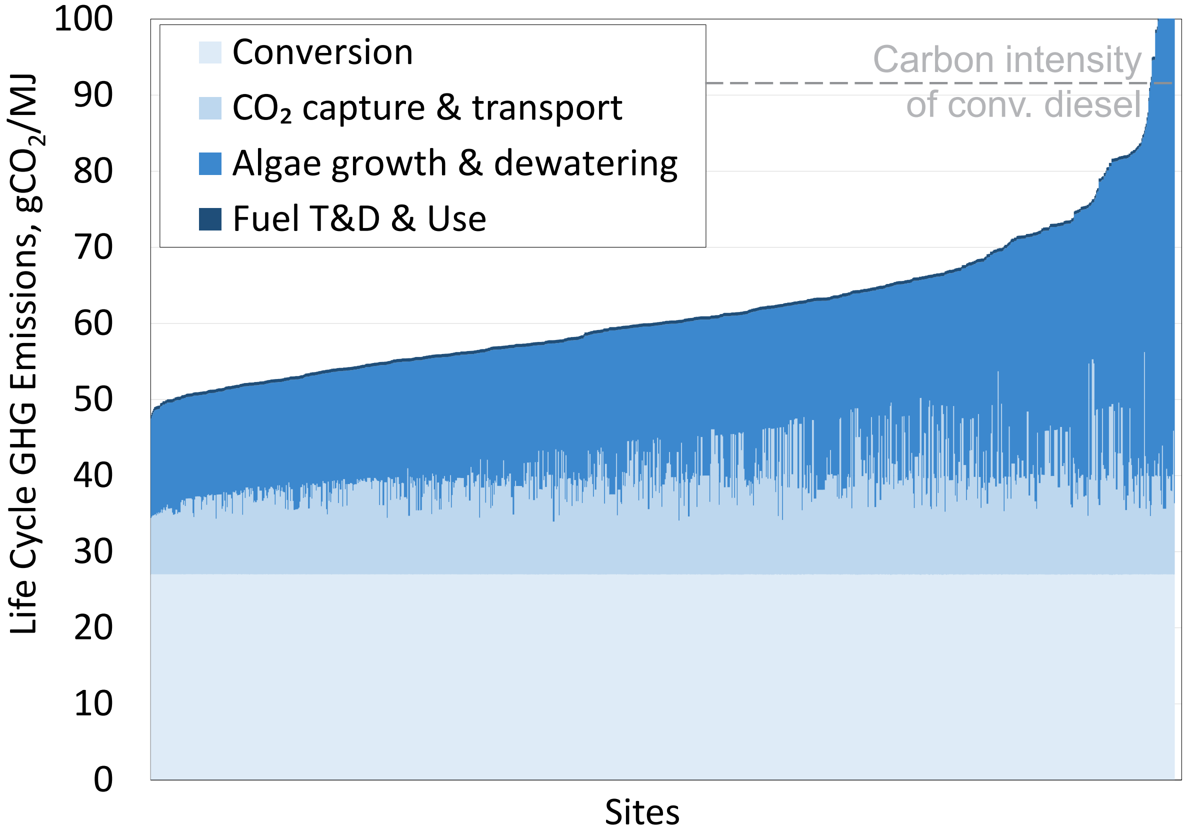
Progress & Outcomes

Cultivating in saline water reduces water stress with GHG tradeoffs

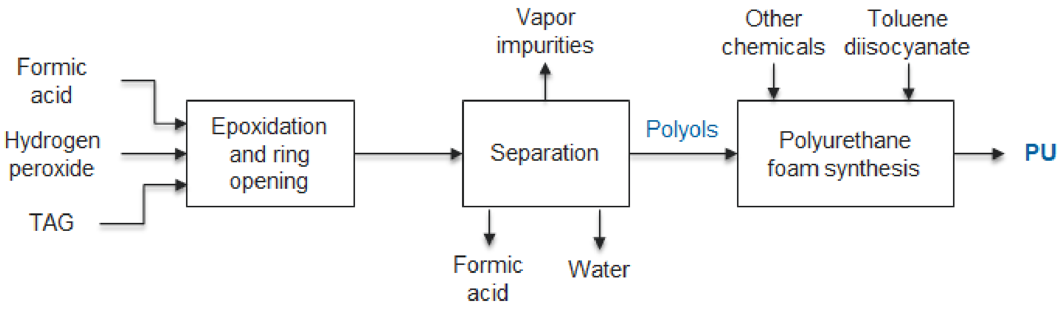
- Significant variation in energy use and GHG across sites.
- Saline aquifer pumping energy and brine management operations tradeoff for avoiding freshwater consumption.
- Finalizing manuscript highlighting “deep dive” high-protein, saline algae analysis.



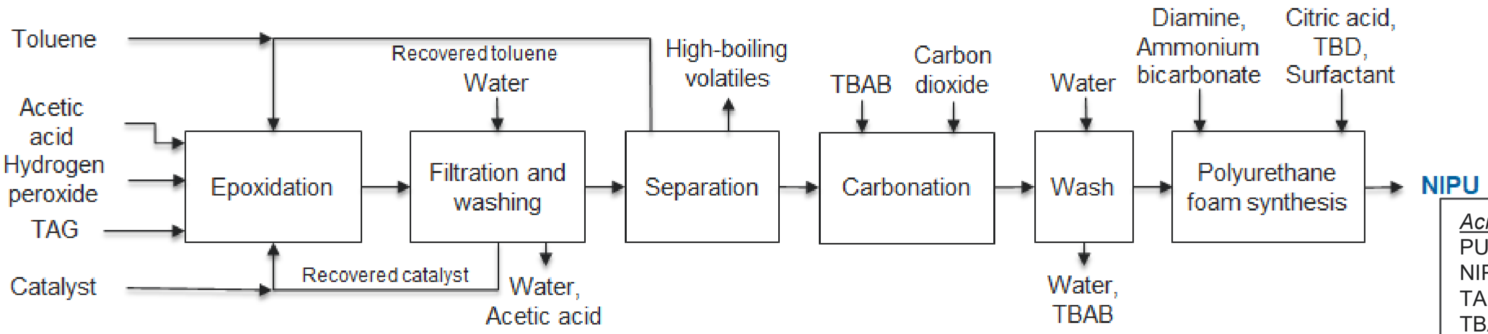
Progress & Outcomes

LCA of Algal Polyurethane Pathways

Conventional polyol/polyurethane production from algal-triglycerides



Production of algae-derived non-isocyanate polyurethane



Analysis leveraging process models developed by NREL TEA team.

LCA in collaboration with Northwestern University through DOE ResIn project.

Acronyms:
PU: Polyurethane
NIPU: Non-isocyanate polyurethane
TAG: Triglyceride
TBAB: Tetrabutylammonium bromide
TBD: Triazabicyclodecene

Impact

3. Impact

LCA contributes to achieving BETO's Advanced Algal Systems goals

Value Proposition of Algal Biofuels/products

- Comprehensively addressing effects of system designs.
- Effects of integration, co-location, and product mix.
- Residual materials can displace energy intensive fertilizers.

Building consensus around benefits.

- Harmonization across BETO and DOE analysis.
- Publicly-available, transparent models accepted by industry.
- Results directly comparable to those for other technologies.

Publishing impactful results.

- Informing BETO of algal biofuels' contribution to biofuel and decarbonization targets.
- Steady track record of peer reviewed publications.

Data and models distributed in GREET releases.

- Interactions with stakeholders around key parameters and industry developments.
- Feeds into influential policies. Over 50,000 users worldwide.

- Benchmarking and tracking R&D progress of pathways to produce low-carbon, sustainable algal biomass.
- Providing comparable, transparent, and reproducible LCA for algal fuel and product pathways.
- Screening algal systems, feedback to BETO R&D and commercialization/scale up decisions.

Impact

Dissemінating Key Results

Informing stakeholders through peer-reviewed journals, conference presentations, reports, and direct interactions.

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ANL/ESD-22/5 Rev. 1

Supply Chain Sustainability Analysis of Renewable Hydrocarbon Fuels via Indirect Liquefaction, Hydrothermal Liquefaction, Combined Algal Processing, and Biochemical Conversion: Update of the 2021 State-of-Technology Cases

Argonne NATIONAL LABORATORY

ANL/ESD-20/1

Summary and Instructions for Monthly AWARE-US Model

Journal of Cleaner Production 321 (2021) 128779

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

ELSEVIER

Utilizing high-purity carbon dioxide sources for algae cultivation and biofuel production in the United States: Opportunities and challenges

Longwen Ou[a], Sudhanya Banerjee[a], Hui Xu[a], André M. Coleman[b], Hao Cai[a], Uisung Lee[a], Mark S. Wigmosta[b], Troy R. Hawkins[a,*]

ARTICLE INFO

Keywords:
Algae
High-purity carbon dioxide
Life-cycle assessment
Greenhouse gas emissions
Water stress

ABSTRACT

Carbon dioxide (CO_2) supply is an important consideration for algae production systems, and using high-purity CO_2 eliminates the need for purification processes. This study assessed the challenges and opportunities inherent in using waste high-purity CO_2 to produce algae in the United States. The United States' upper Midwest region is rich in high-purity CO_2 from corn ethanol production. However, its climate is not as favorable for algae production as that on the Gulf Coast. This study assessed the tradeoffs between these factors by comparing algae

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ANL/ESIA-22/1

Summary of Expansions and Updates in GREET® 2022

ANL-23/XX
NREL/TP-XXXX-XXXX
PNNL-XXXXX

Economic, Greenhouse Gas, and Resource Assessment for Fuel and Protein Production from Microalgae

2022 Algae Harmonization Update

Argonne National Laboratory
National Renewable Energy Laboratory
Pacific Northwest National Laboratory

UNDER REVIEW

2022 ALGAE BIOMASS SUMMIT

Argonne NATIONAL LABORATORY

IMPLICATIONS OF CO_2 SOURCING ON THE COSTS AND LIFE-CYCLE GREENHOUSE GAS EMISSIONS OF ALGAE BIOFUELS

Udayan Singh, Sudhanya Banerjee, Troy Hawkins
Fuels and Products Group
Argonne National Laboratory

10/10/2022

ALGAE BIOMASS SUMMIT

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Environmental Science & Technology

pubs.acs.org/est — Policy Analysis

Balancing Water Sustainability and Productivity Objectives in Microalgae Cultivation: Siting Open Ponds by Considering Seasonal Water-Stress Impact Using AWARE-US

Hui Xu,* Uisung Lee, André M. Coleman, Mark S. Wigmosta, Ning Sun, Troy Hawkins, and Michael Wang

Cite This: Environ. Sci. Technol. 2020, 54, 2091−2102

ACCESS | Metrics & More | Article Recommendations | Supporting Information

ABSTRACT: Microalgae have great potential as an energy and feed resource. Here we evaluate the water use associated with freshwater algae cultivation and find it is possible to scale U.S. algae

Algae growth model
Land and CO_2
Potential sites

ACS Sustainable Chemistry & Engineering

pubs.acs.org/journal/ascecg — Research Article

Life-Cycle Assessment of Biochemicals with Clear Near-Term Market Potential

Chao Liang, Ulises R. Gracida-Alvarez, Troy R. Hawkins,* and Jennifer B. Dunn*

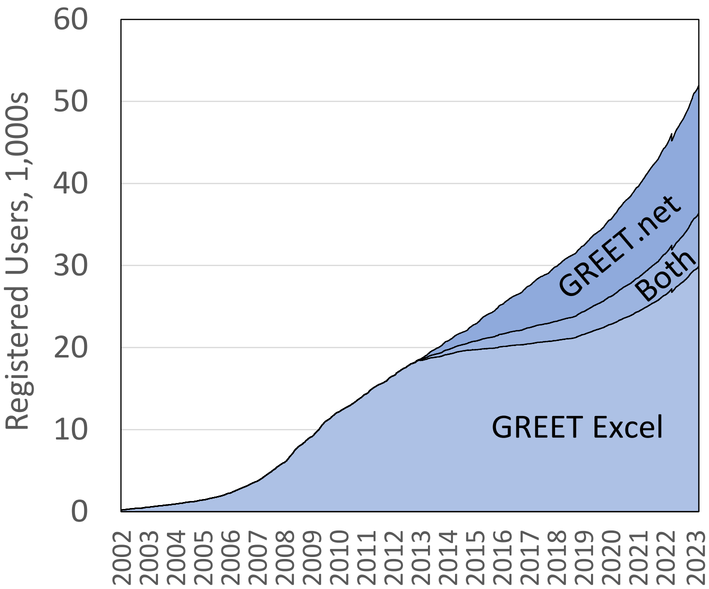
Cite This: ACS Sustainable Chem. Eng. 2023, 11, 2773−2783

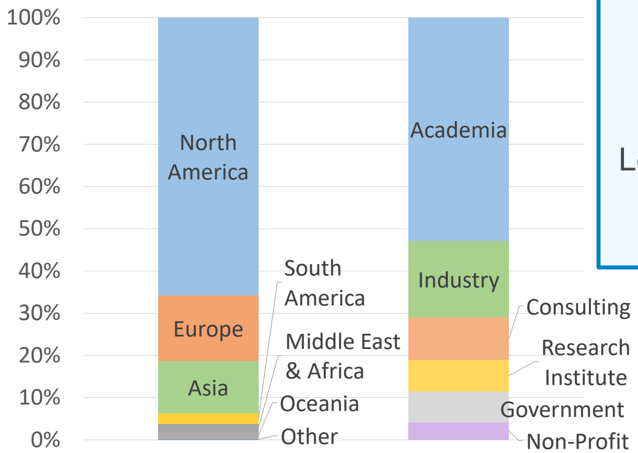
ACCESS | Metrics & More | Article Recommendations | Supporting Information

ABSTRACT: The urgent need for greenhouse gas (GHG) emission reductions to mitigate climate change calls for accelerated biorefinery development and biochemical deployment to the market as structural or functional replacements for chemicals produced from fossil-derived feedstocks. This study evaluated the energy and environmental impacts of 15 biochemicals with clear near-term

Impact

Models disseminated through GREET releases





50,000+ registered users worldwide

Used for Low Carbon Fuel Standard and Renewable Fuel Standard pathway analyses

Impact

GREET Informs Policy and Regulation

- **California-GREET** is an adaptation of Argonne's GREET model
- Specified in **Inflation Reduction Act** related to the **Clean Fuel Production Credit** and the **Clean Hydrogen Credit**
- **U.S. EPA** uses GREET with other sources for **Renewable Fuels Standard** pathway evaluations
- **Oregon Clean Fuels Program** also uses an adaptation of Argonne's GREET model
- **National Highway Traffic Safety Administration** for fuel economy regulation
- **Federal Aviation Administration** and **International Civil Aviation Organization** using GREET to evaluate aviation fuel pathways
- **U.S. Maritime Administration - renewable marine fuel options for IMO 2020 sulfur limits**
- **U.S. Dept. of Agriculture bioenergy LCA** and carbon intensity of farming practices
- **Canadian Clean Fuel Standard** for Environment and Climate Change Canada fuel pathways

Summary

Overview	• Quantify life-cycle energy and environmental metrics for strategic algal biofuel and bioproduct systems.
Approach	• Focused on key questions. • Clear objectives, strong team, organized task structure, well defined milestones, regular communication. • Harmonization across BETO algal systems analysis efforts, interacting with PNNL, NREL, INL, and NETL to harmonize and leverage efforts. • Incorporating new models to address key aspects of algal pathways.
Impact	• Presenting value proposition for algal biofuel and bioproduct technologies. • Building consensus around the GHG and other environmental impacts of algal biofuels. • Publishing peer reviewed journal articles, engaging with stakeholders. • Data and models distributed publicly in annual GREET releases.
Progress & Outcomes	• Contributions to BETO algal biofuel pathway benchmarking via supply chain sustainability analyses. • LCA considering a wide range of CO_2 sources reveals biogenic and direct air capture CO_2 more consistent with decarbonization than fossil CO2. • LCA of tradeoffs of using high-purity CO_2 in Midwest and Gulf Coast locations. • Completed LCA for BETO algae harmonization analysis and prepared report. • Performed detailed LCA of saline algae production systems and protein coproducts.

Quad Chart Overview

LCA of Advanced Algal Systems

Timeline

Oct. 1, 2020 – Sep. 30, 2023

	FY22	Total Award
DOE Funding	*$200,000*	*$700,000*
Cost Share	*N/A*	*N/A*

Project Partners

- M. Wigmosta, A. Coleman, PNNL: Algae Resource Analysis (1.3.5.203)
- R. Davis, NREL: Algae Technoeconomic Analysis (1.3.5.200)
- L. Snowden-Swan, PNNL: HTL Technoeconomic Analysis
- T. Skone, NETL: FECM CO_2 Utilization
- D. Hazlebeck, Global Algae

Project Goal

(1) Inform R&D decisions by BETO and its stakeholders with detailed energy and environmental LCA of advanced algal systems and strategic case studies
(2) Provide LCA results and datasets for key algae production and conversion pathways to benchmark the state of technologies and evaluate the relative performance of alternative designs and algae R&D advancements.

End of Project Milestone

Reports on LCA results for saline algae, CO_2 sources, algal bioproduct, and integration with wastewater/manure management. Models/data in annual GREET releases.

Funding Mechanism

BETO FY2020 Lab Call (Annual Operating Plan)

Publications

Peer reviewed reports and articles

Ou L, Banerjee S, Xu H, Coleman AM, Cai H, Lee U, Wigmosta MS, Hawkins TR. 'Utilizing High-Purity CO_2 Sources for Algae Cultivation and Biofuel Production in the United States: Opportunities and Challenges.' *J of Cleaner Production.* **2021**. 321. 128779. https://doi.org/10.1016/j.jclepro.2021.128779

Singh U, Banerjee S, Hawkins TR. 'Implications of CO_2 Sourcing on the Costs and Global Warming Potential of Microalgal Biofuels.' *Sustainable Chemistry & Engineering.* **2023**. In review.

Cai H, Ou L, Wang M, Davis R, Dutta A, Harris K, Wiatrowski M, Tan E, Bartling A, Klein B, Hartley D, Burli P, Lin Y, Roni M, Thompson D, Snowden-Swan L, Zhu Y, Li S. 'Supply Chain Sustainability Analysis of Renewable Hydrocarbon Fuels via Indirect Liquefaction, Hydrothermal Liquefaction, Combined Algal Processing, and Biochemical Conversion: Update of the 2021 State-of-Technology Cases.' Argonne National Laboratory. Lemont, Illinois. **2022**. ANL/ESD-22/5.

Liang C, Gracida U, Hawkins TR, Dunn JB. 'Life-Cycle Assessment of Biochemicals with Clear Near-Term Market Potential.' *Sustainable Chemistry & Engineering.* **2023**. 11(7) 2773-2783. https://doi.org/10.1021/acssuschemeng.2c05764

Zhang J, Zhu Y, Coleman AM, Klein B, Singh U, Ou L, Hawkins TR. 'County-Level LCA of Saline Microalgal Biofuel and Bioproducts via Hydrothermal Liquefaction.' For submission in FY23.

Presentations

Disseminating results to stakeholders

Singh U, Banerjee S, Hawkins TR. 'Implications of CO2 Sourcing on the Costs and Life-Cycle Greenhouse Gas Emissions of Algal Biofuels.' Presented at the *2022 Algae Biomass Summit.* (Virtual) and the *2022 American Geophysical Union Fall Meeting*, Chicago, Illinois.

Singh U, Banerjee S, Hawkins TR. 'Environmental and economic Efficacy of Algal Biofuels as a CO2 Capture and Utilization Strategy.' *2022 Informs Annual Meeting.* Indianapolis, Indiana.

Banerjee S, Xu H, Coleman A, Yan H, Wigmosta M, Hawkins TR. 'Assessment of the Energy Use, Greenhouse Gas Emissions, and Water Stress Associated with Saline Algae Cultivation and Conversion in the United States.' *2021 Algae Biomass Summit*. (Virtual).

Banerjee S, Ou L, Xu H, Coleman A, Cai H, Lee U, Wigmosta M, Hawkins TR. 'Assessment of the Energy Use, Greenhouse Gas Emissions, and Water Stress Associated with Growing Algae Using High-Purity Carbon Dioxide Sources in the Midwest and Along the Gulf Coast of the United States.' *2020 Algae Biomass Summit*. San Diego, California.

Hawkins TR, Elgowainy A, Lee U, Benavides PT, Cai H, Zang G, Sun P, Banerjee S, Xu H, Wang M. 'Bioproducts, Algae Pathways, and CO2 Utilization in the GREET Model. U.S. Dept. of Energy, Office of Fossil Energy and Carbon Management and Other Stakeholders.

Hawkins TR, Cai H. 'GREET Life Cycle Analysis of Bioenergy Technologies.' 2022 GREET User Workshop. Lemont, Illinois.

Responses to Selected 2021 Peer Review Comments

2021 Peer Review Comment	*Response*
How often the project team is meeting is not clear, and risk and mitigation strategies do not appear to be addressed. … The approach described seems to lack a technical validation component where assumptions can be tested, and modeled results can be verified.	We thank the reviewers for recognizing the value of this work. It is very nice to hear that it is an essential part of the program and that the products have clear value for a broad range of consumers. The reviewer's point about better describing the potential risks and mitigation strategies is well taken, and as mentioned, validation of our models is a key risk that we have taken steps to mitigate. The team meets weekly to discuss progress and troubleshoot issues that arise. The Argonne team works closely with PNNL's algae resource assessment and hydrothermal liquefaction conversion TEA efforts and NREL's algae farm and combined algal processing TEA projects to leverage data and model outputs across the teams. The beauty of the depth of analysis happening across the BETO portfolio and the coordination amongst the projects is that values that have been deeply vetted in the context of one effort can be leveraged for another. Both PNNL and NREL have been engaged with us on the LCA of saline algae production. Outside of this project, many of the same researchers collaborate through BETO's annual SOT and target case benchmarking efforts. We also regularly review the literature to vet the values used in our analyses against those reported in outside studies. We have found that the interaction of LCA with other process modeling, TEA, and resource assessment efforts provides natural opportunities for quality assurance across projects. Finally, Task 5 in our project is specifically dedicated to harmonization across BETO's TEA, LCA, and resource assessment projects. In addition, the Argonne team has engaged with an industry partner to collaborate on the FY 2022 analysis of algae products and who will also provide field measurements. In parallel, Argonne staff are also participating in another algae technology development project led by University of Maryland and funded by the Office of Fossil Energy, which provides valuable additional perspectives to this effort.

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How often the project team is meeting is not clear, and risk and mitigation strategies do not appear to be addressed.	Another risk we have encountered is schedule slip, specifically associated with data hand-offs across labs. We have mitigated this risk through close communication and staged data hand-offs to allow us to have the analysis routines in place in advance. Along with schedule slip is the risk of working inefficiently, which we have mitigated by having parallel tracks in the analysis so one can always be advanced if the other is on hold. We appreciate the reviewers' positive response to our work and will continue to strive to produce rigorous analyses useful for informing research and development of advanced algal systems and, as collateral, tools that make the analyses transparent and allow others to replicate and extend the results.

Project Timeline