Life Cycle Analysis of Advanced Algal Systems

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Systems Assessment Center
Argonne National Laboratory
WBS #1.3.5.204

2021 BETO Peer Review
March 10, 2021

PROJECT OVERVIEW

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 algae analysis efforts • Provide LCA tool to bioeconomy and LCA community
Relevance	**Addresses BETO goals for increasing the supply of sustainable algae** (Aft-A) **and reducing the resource intensity of production** (Aft-B), **including system integration** (Aft-H) **and resource recycling** (Aft-J)	• 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/

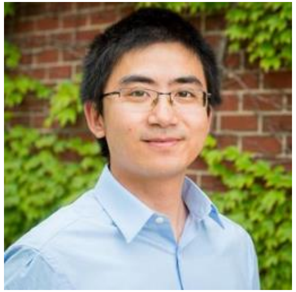
1. MANAGEMENT

1. Management

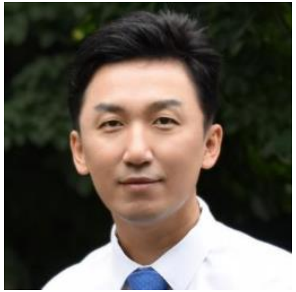
Project team with diverse expertise to address varied aspects of algal systems

Troy Hawkins
Project Lead

Sudhanya Banerjee
Post-Doctoral Researcher



Hao Cai
SCSA Lead



Uisung Lee
Sr. Analyst

Longwen Ou
Energy Systems Analyst

Hui Xu
Energy Systems Analyst

1. Management

Tasks are structured with clear objectives

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.
2. **Comparison of CO_2 sources for algae cultivation including direct air capture**
   - Evaluate the life cycle energy and environmental implications of options for CO_2 sources for algae production.
3. **LCA of algae-based bioproducts**
   - Understand the benefits and tradeoffs of pathways for producing valuable products from algae through comparison with conventional pathways.
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 Technoeconomic Analysis, LCA, and Resource Assessment**
   - Coordinate and harmonize technoeconomic analysis, LCA, and resource assessment activities within BETO's Advanced Algal Systems program.

1. Management

Interact with other relevant project teams to harmonize and leverage efforts

Algal Biomass Production R&D

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

Algal Biomass Availability Assessment

Pacific Northwest
NATIONAL LABORATORY

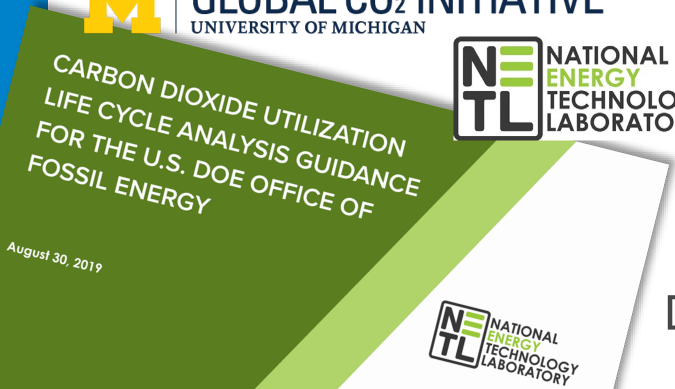
Conversion Process Modeling Techno-Economic Analysis

Algae Farm Cost Modeling

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

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

Argonne NATIONAL LABORATORY 75 1946–2021

1. Management

Clear management plan and 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

2. APPROACH

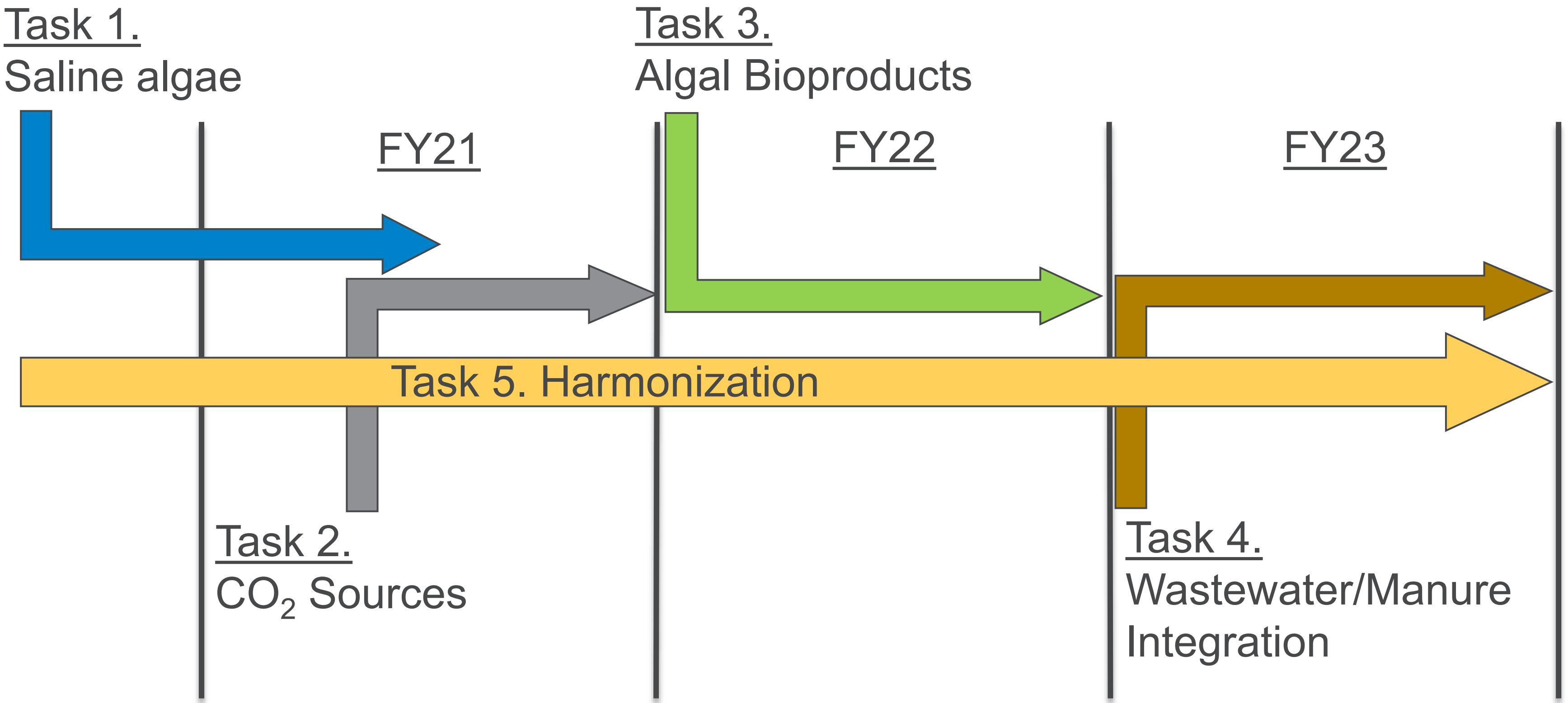
2. Approach

Focused on key questions for understanding life cycle metrics for algal systems

Task	*Key questions and new considerations*
1. LCA of saline algae production systems	• Can saline algae production alleviate water stress? How do LCA for saline algae production systems compare with other pathways? • 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	• How do different CO_2 sources affect LCA metrics for algae production? • CO_2 sources incl. coal and natural gas combustion; high-purity sources such as steam methane reforming, biogas, and fermentation; and direct air capture. Leveraging NETL datasets on CO_2 capture and logistics.
3. LCA of algae-based bioproduct pathways	• What are the environmental benefits and tradeoffs of high-value products from algal biomass? • Higher-value products and co-products improve economics and promote commercialization of algae cultivation systems.
4. Integration of algae cultivation with wastewater and manure mgt	• How could algae contribute to reducing the life cycle impacts of wastewater/manure treatment while producing valuable fuels & products? • Using nutrient-rich wastewater streams, e.g. centrate, AD wastewater, and integration with high-purity CO_2 from AD and heat sources.

2. Approach

Project timeline



<u>Task 1.</u>
Saline algae

<u>Task 3.</u>
Algal Bioproducts

<u>FY21</u>

<u>FY22</u>

<u>FY23</u>

Task 5. Harmonization

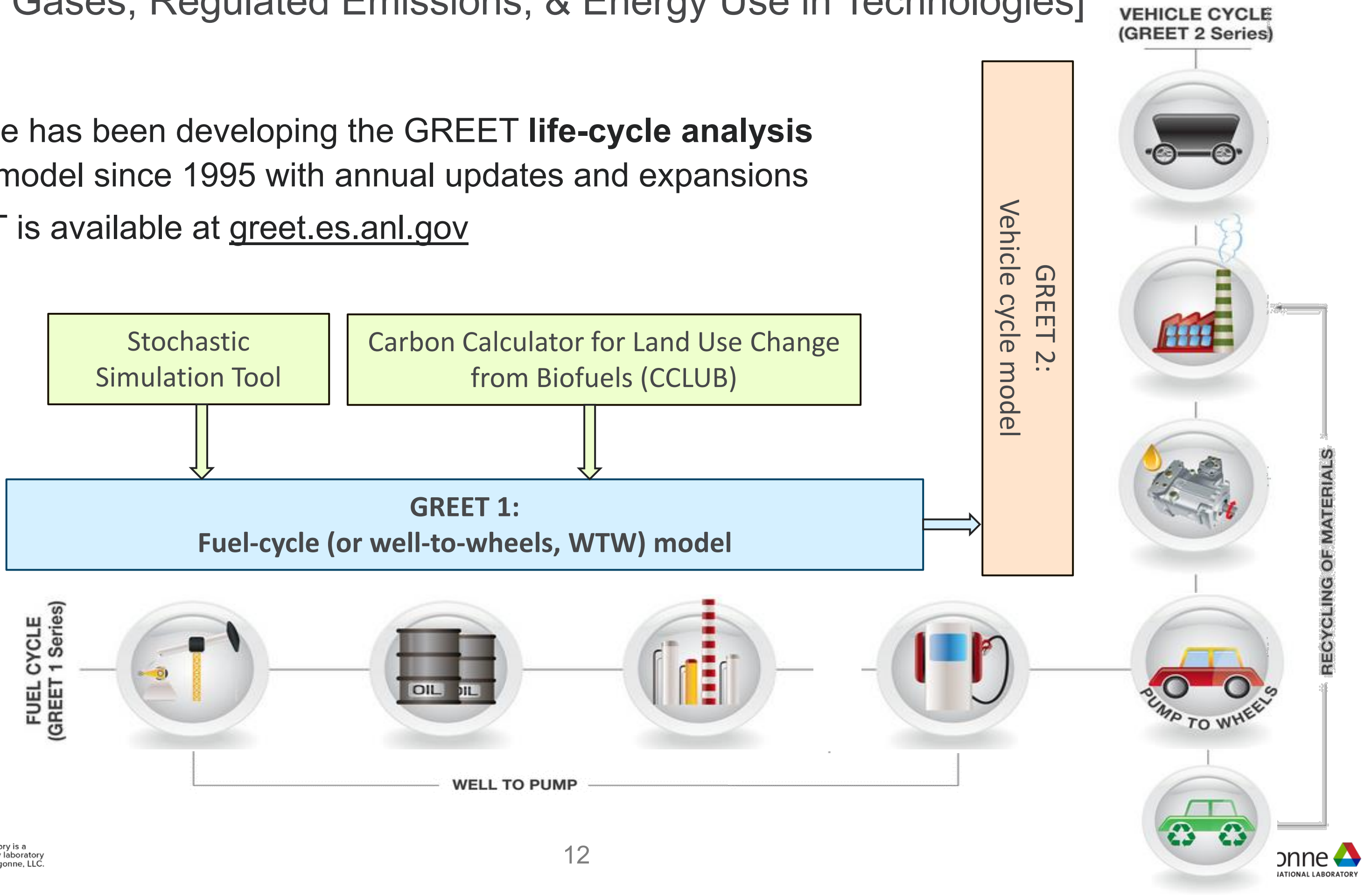
<u>Task 2.</u>
CO_2 Sources

<u>Task 4.</u>
Wastewater/Manure Integration

2. 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



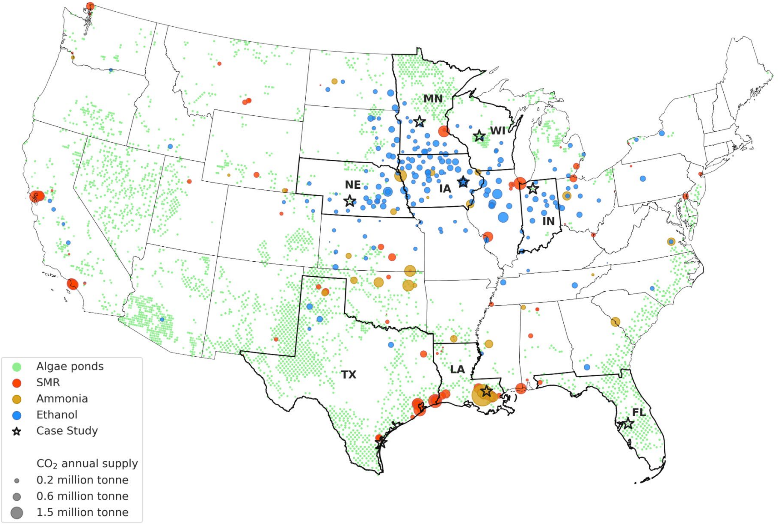
Stochastic Simulation Tool

Carbon Calculator for Land Use Change from Biofuels (CCLUB)

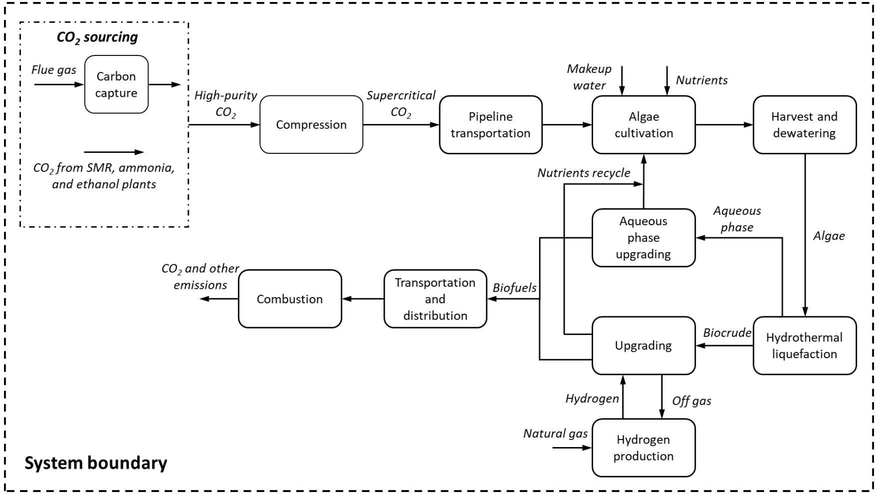
GREET 1:
Fuel-cycle (or well-to-wheels, WTW) model

GREET 2:
Vehicle cycle model

3. Approach Exploring how high-purity CO_2 can improve the environmental profile of algae cultivation in partnership with Pacific Northwest National Laboratory



- High-purity CO_2 sources
  - Ammonia production
  - Steam methane reforming
  - Corn ethanol fermentation
- Life-cycle environmental metrics
  - GHG emissions
  - Freshwater consumption/water stress
  - Fossil energy use



- Selected sites in two regions with abundant high-purity CO_2:
  - Gulf Coast industrial cluster, ammonia & SMR facilities
  - Midwest corn ethanol plants

3. IMPACT

3. Impact

LCA contributes to achieving BETO's Advanced Algal Systems goals

Biomass Availability and Cost (Aft-A)

- Lack of sufficient data on potential … location, seasonality, environmental sustainability… of algal biomass feedstock creates uncertainty.

Sustainable Algae Production (Aft-B)

- The productivity, energy use, and environmental effects of algae production and harvest systems have not been comprehensively addressed.

Integration (Aft-H)

- Potential for co-location with other related bioenergy technology to improve balance of plant costs and logistics.

Resource Recapture and Recycle (Aft-J)

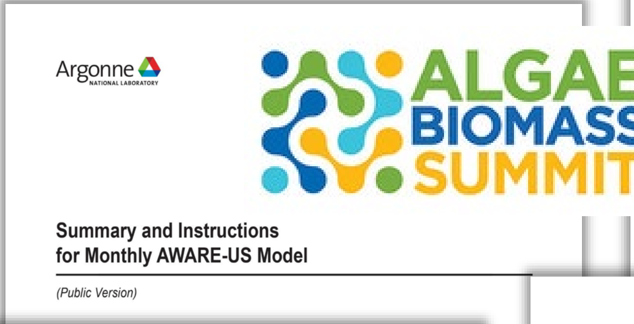
- Residual materials can displace fertilizer inputs.

- 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.

3. Impact

Publication and dissemination

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

Summary and Instructions for Monthly AWARE-US Model

(Public Version)


Argonne NATIONAL LABORATORY

ANL/ESD-

Supply Chain Sustainability Analysis of Renewable Hydrocarbon Fuels via Indirect Liquefaction, Ex Situ Catalytic Fast Pyrolysis, Hydrothermal Liquefaction, Combined Algal Processing, and Biochemical Conversion: Update of the 2019 State-of-Technology Cases


Algal Research 37 (2019) 30–39

Contents lists available at ScienceDirect

Algal Research

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

ELSEVIER

Assessment of algal biofuel resource potential in the United States with consideration of regional water stress

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ARTICLE INFO

Keywords:
Algae
Biofuel
Renewable energy
Water scarcity footprint
Water use
Sustainability

ABSTRACT

Algae is a promising feedstock for biofuels. Because scaling up the production of algae-based biofuels consumes a significant amount of water, it is important to consider the impact it has on water stress. This study evaluates the potential for algae-derived biofuel production in the United States (US) and considers regional water stress. We used the Biomass Assessment Tool (BAT) to identify potential sites in the US that meet land, biomass productivity, and CO_2 co-locating criteria. We quantify the water stress impacts of algal biofuel production in terms of water scarcity footprint using water consumption from BAT, and the water stress indicator from Available Water Remaining for the US (AWARE-US) system. We assess long-term (20 billion gal per year [BGY]) and near-term (5 BGY by 2030) renewable diesel (RD) production targets. To select suitable algae sites, we consider biomass yield and water use with and without water stress constraints. We found that ranking sites based on biomass yield results in a high water stress impact (24.5×10^3 US equivalent BGY [BGYe]) for the long-term RD
s on average by 62%, with an
ass yield and water stress im-
lity by region can be applied
ressed areas and keeps high-
by 55% (13.8 BGYe) without
o the sites ranked by biomass
cale algae biofuel production
ss impacts.

ofuels in the United States
ear (BLY). However, algae-
intensity than petroleum-
water resources is rapidly
uding energy production,
valuated in the context of
uses [8]. For sustainable
of algae cultivation facil-
n fuel yields and low water

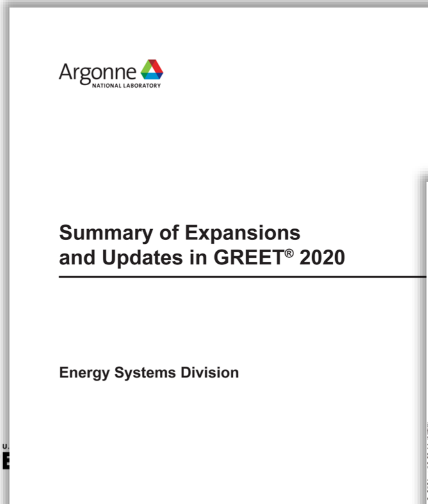
otential from algae in the
and economics [4,6,7,9].
stress impacts for algae
aluated the availability of
he United States; they de-
se ≤5% of the long-term


U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

BIOENERGY TECHNOLOGIES OFFICE

Multi-Year Program Plan

March 2016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ANL/ESD-20/9

Summary of Expansions and Updates in GREET® 2020

Energy Systems Division


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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

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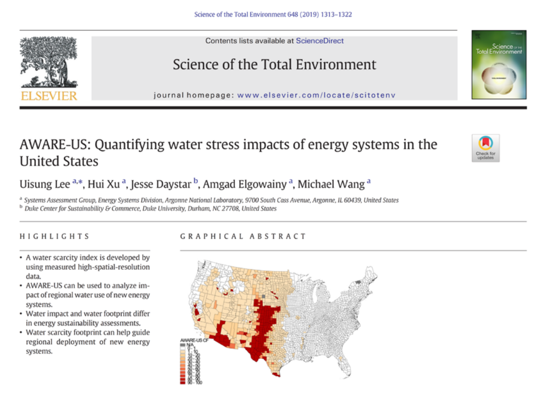
ABSTRACT: Microalgae have great potential as an energy and feed resource. Here we evaluate the water use associated with freshwater algae cultivation and find it is possible to scale U.S. algae biofuel production to 20.8 billion liters of renewable diesel annually without significant water-stress impact. Among potential sites, water-stress is significantly more variable than algae productivity


Science of the Total Environment 648 (2019) 1313–1322

Contents lists available at ScienceDirect

Science of the Total Environment

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

ELSEVIER

AWARE-US: Quantifying water stress impacts of energy systems in the United States

Uisung Lee[a,*], Hui Xu[a], Jesse Daystar[b], Amgad Elgowainy[a], Michael Wang[a]

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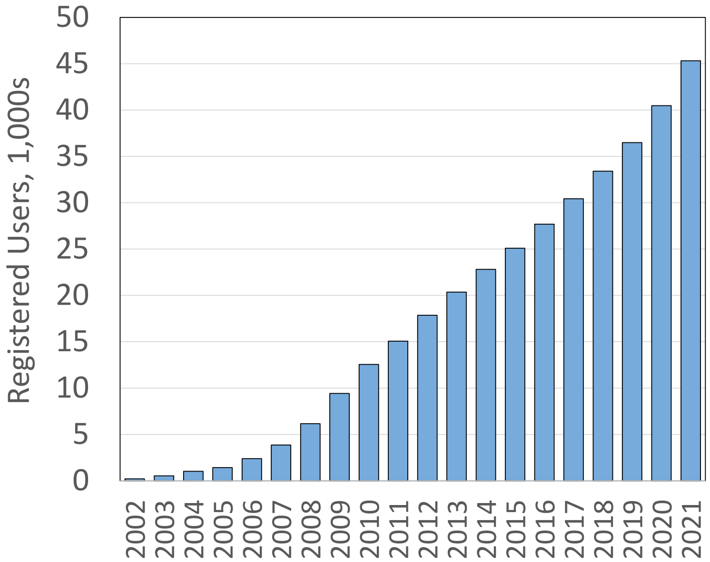
HIGHLIGHTS

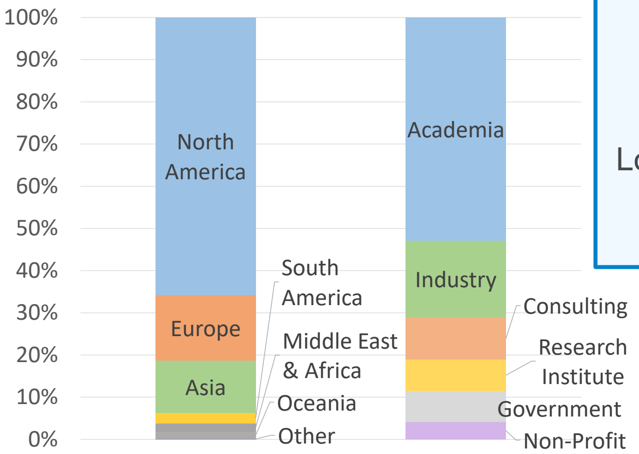
- A water scarcity index is developed by using measured high-spatial-resolution data.
- AWARE-US can be used to analyze impact of regional water use of new energy systems.
- Water impact and water footprint differ in energy sustainability assessments.
- Water scarcity footprint can help guide regional deployment of new energy systems.

GRAPHICAL ABSTRACT

3. Impact

Models developed through the project disseminated through annual GREET releases





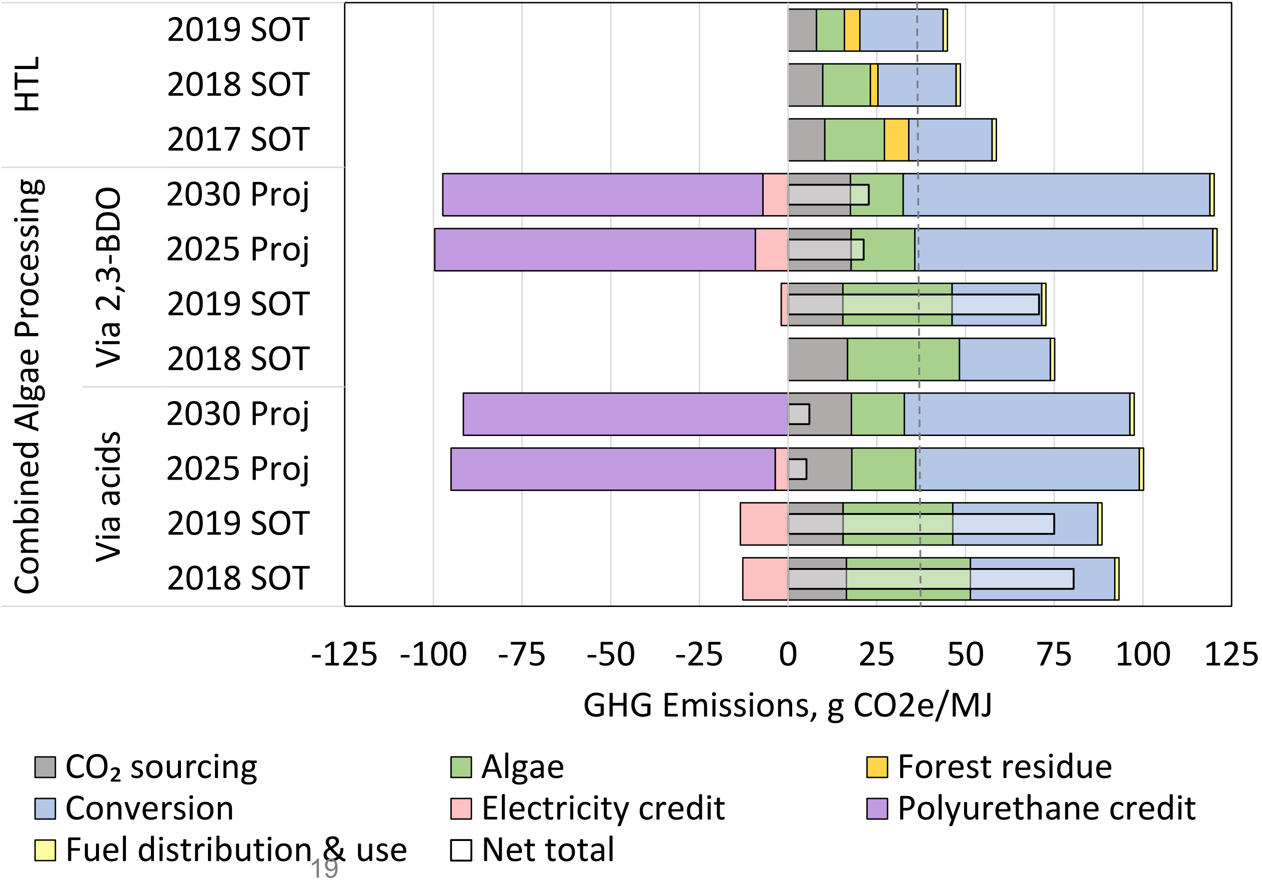
45,000+ registered users worldwide

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

4. PROGRESS AND OUTCOMES

4. Progress and Outcomes Supply chain sustainability analyses track progress and identify opportunities for improving sustainability of algal biofuel pathways

- Improvements in algal productivity driving improvements in state of technology benchmark.
- Polyurethane co-product significant affects GHG results for biofuel from combined algal processing pathway.



(Cai et al., 2020)

4. Progress and Outcomes

Created AWARE-US for water 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.*)

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

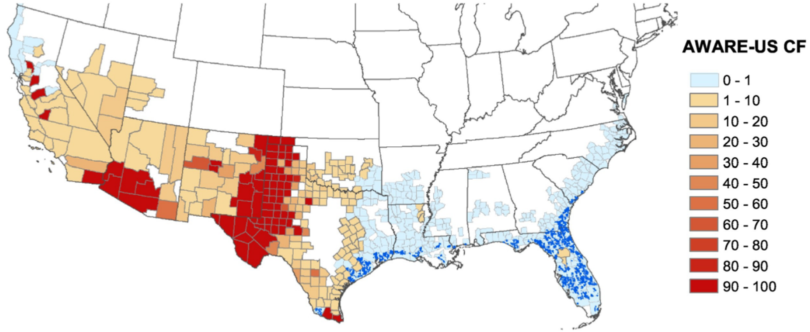
CF: characterization factor

Lee et al. (2019) *AWARE-US: Quantifying Water Stress Impacts of Energy Systems in the United States*

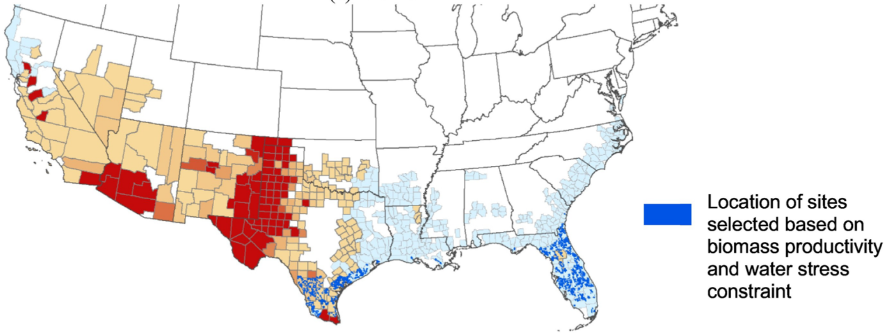
4. Progress and Outcomes

Applied AWARE-US to guide sustainable scale up of algae farms

- Water consumption misses geographic differences in water availability
- Choosing sites based on AWARE-US water stress rather than productivity and CO_2 source alone
  - 45% less water consumption and
  - 97% less water stress
  - only 4% lower yield



(a) CF< 1



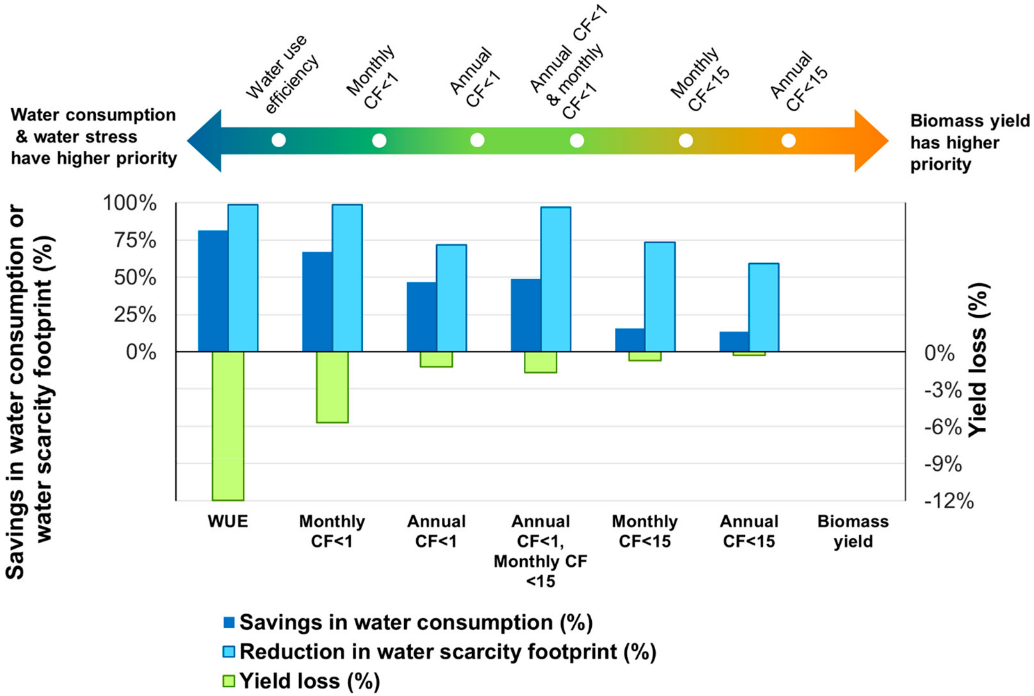
(b) CF< 20

Xu et al. (2019) *Assessment of Algal Biofuel Resource Potential in the United States with Consideration of Regional Water Stress*

4. Progress and Outcomes

Incorporated seasonal water considerations into algae site screening and AWARE US

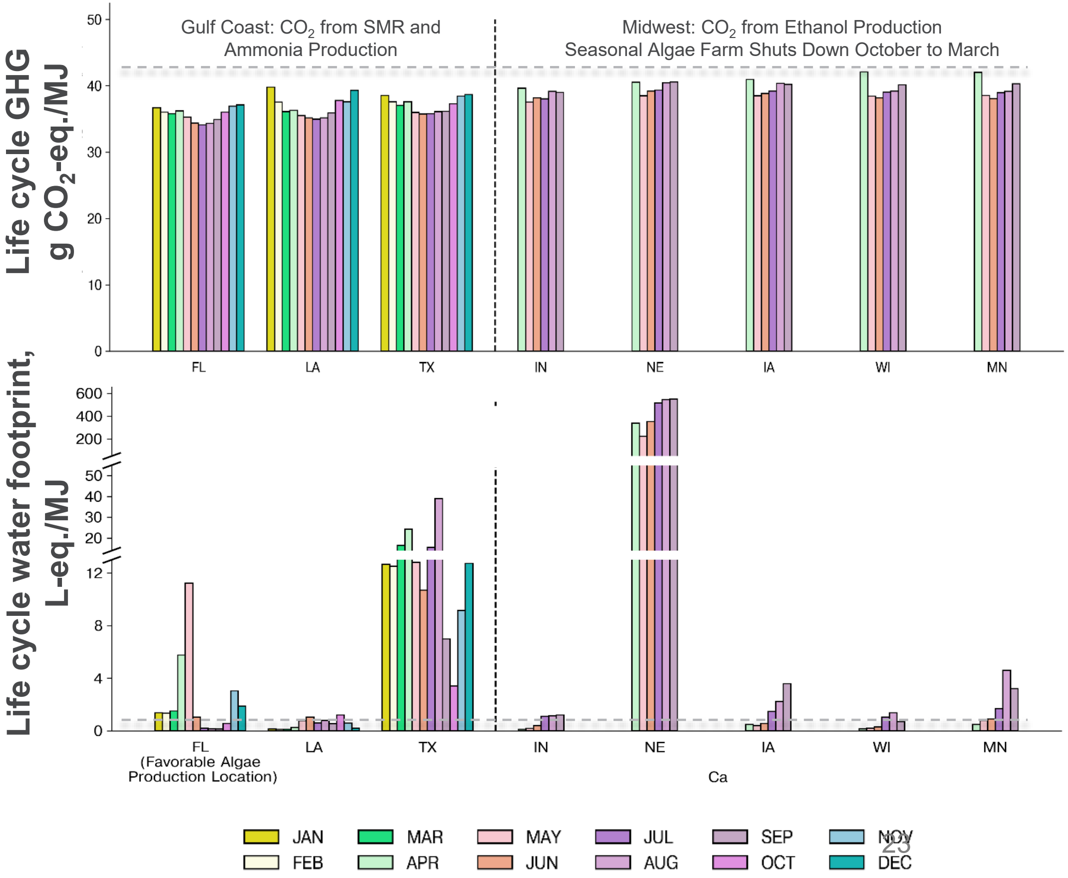
- Considering seasonal water balances is important to limit risks of short-term water shortages and operational interruptions
- There are tradeoffs among yield and water objectives; considering both annual and seasonal water impact can achieve balanced performance
- Algae biofuel could meet 19.7% of U.S. jet fuel demand with less than 1.4% of U.S. irrigation consumption



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*

4. Progress and Outcomes

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



- **GHG emissions per MJ for Midwest comparable to southern sites April-September.**
- Conversion facility could run with feedstocks such as forest residuals or stover in off-months.
- Some Midwest sites have favorable water availability compared with Texas and Florida.
  - Pattern of lower water supply in late summer/early fall in Midwest.
  - Nebraska illustrates importance of water stress screening.

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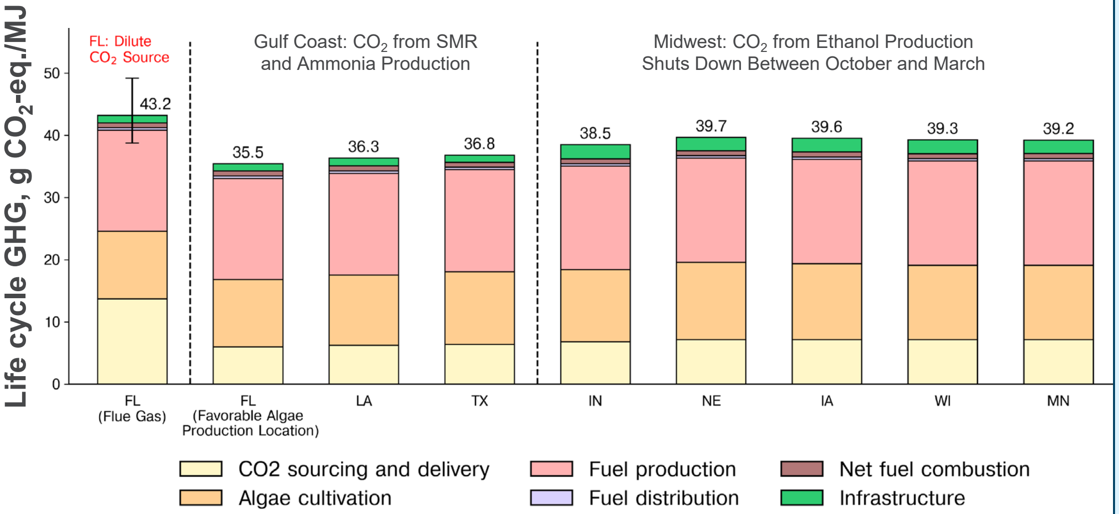
4. Progress and Outcomes

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

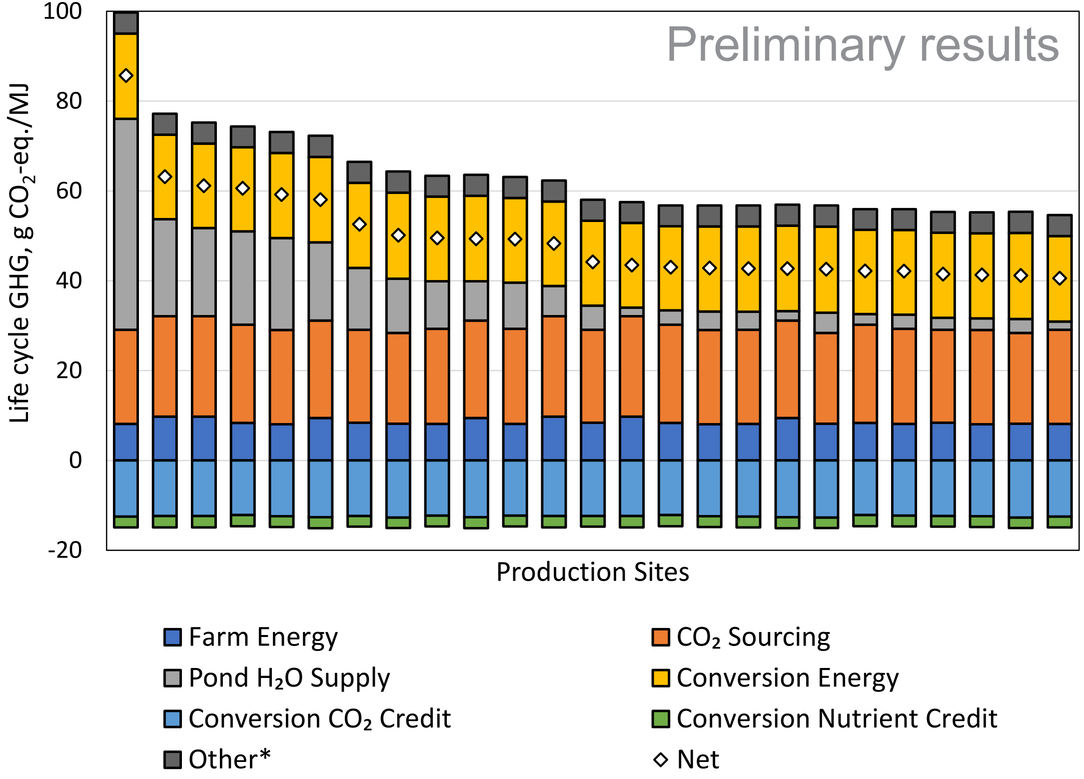


- **GHG emissions per MJ for Midwest sites with high-purity CO_2 perform better than favorable conditions in Florida with combustion CO_2 source.**
- Ethanol production offers abundant high-purity CO_2 in Midwest
- Ammonia and steam methane reforming provide high-purity CO_2 in Texas and Louisiana
- No high-purity CO_2 sources identified in Florida

4. Progress and Outcomes

In progress: growing algae in saline water could reduce water stress with GHG tradeoffs

- Need to minimize energy for pumping from saline aquifer to manage GHG emissions.
- Significant variation in energy use and GHG across sites
- Developing method for calculating water stress based on salinity relative to seawater.



Other* - Farm nutrients, conversion chemicals, Fuel transport & distribution

3. SUMMARY

Summary

Overview	• Quantify life-cycle energy and environmental metrics for algal biofuels and bioproducts
Management	• Clear objectives, strong team, organized task structure, well defined milestones, regular communication • Interacting with PNNL, NETL, NREL, INL to harmonize and leverage efforts
Approach	• Focused on key questions • Incorporating new models to address key aspects of algal pathways • Harmonization across BETO algal systems analysis efforts
Impact	• Presenting value proposition for algal biofuel and bioproduct technologies • Publishing peer reviewed journal articles, engaging with stakeholders • Data and models distributed publicly in annual GREET releases
Progress & Outcomes	• LCA of tradeoffs of using high-purity CO_2 in Midwest and Gulf Coast locations • Series of studies considering water sustainability in siting algal production systems, AWARE US model • LCA of saline algae production systems

Quad Chart Overview

Timeline

Oct. 1, 2020 – Sep. 30, 2023

	FY2020	Active Project
DOE Funding	*$200,000*	*$600,000*

DOE Partner Labs

PNNL 1.3.5.203 (Wigmosta)
NREL 1.3.5.200 (Davis)
NETL (Skone)

Barriers Addressed

Aft-A. Biomass availability and cost
Aft-B. Sustainable algae production
Aft-H. Integration
Aft-J. Resource recapture and recycle
At-E. Quantification of economic, environmental, and other benefits and costs

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 release.

Funding Mechanism

Lab call/Annual Operating Plan

Publications

Peer reviewed journal articles

Lee, U.; Xu, H.; Daystar, J.; Elgowainy, A.; Wang, M. 'AWARE-US: Quantifying Water Stress Impacts of Energy Systems in the United States.' *Science of the Total Environment* **2019**, *648*, 1313–1322. https://doi.org/10.1016/j.scitotenv.2018.08.250.

Xu, H.; Lee, U.; Coleman, A. M.; Wigmosta, M. S.; Wang, M. 'Assessment of Algal Biofuel Resource Potential in the United States with Consideration of Regional Water Stress.' *Algal Research* **2019**, *37*, 30–39. https://doi.org/10.1016/j.algal.2018.11.002.

Xu, H.; Lee, U.; Coleman, A. M.; Wigmosta, M. S.; Sun, N.; Hawkins, T.; Wang, M. 'Balancing Water Sustainability and Productivity Objectives in Microalgae Cultivation: Siting Open Ponds by Considering Seasonal Water-Stress Impact Using AWARE-US.' *Environmetnal Science and Technology* **2020**, *54* (4), 2091–2102. https://doi.org/10.1021/acs.est.9b05347.

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.' *In review at Environmental Science and Technology.*