DOE Bioenergy Technologies Office (BETO) 2023 Project Peer Review

Algal Biofuels Techno-Economic Analysis – 1.3.5.200

April 4, 2023
Advanced Algal Systems Session
Ryan Davis
NREL

Project Overview

Goal:

- Provide **process design and economic analysis support** for the algae platform to **guide R&D priorities** to commercialization
  - Translate demonstrated/proposed research advances into economics (quantified as $/ton biomass or $/gal fuels)

Outcomes:

- Benchmark process models and economic analysis tools – used to:
  - Assess cost-competitiveness and **establish process/cost targets** for algal biofuel process scenarios, **synch with LCA** (ANL)
  - **Interface** with DISCOVR to support operational baseline TEA beyond nth-plant models, iterate with tech. advisory board
  - Evaluate near-term opportunities for **today's algae industry** on existing resources (protein, wastewater, algal blooms, …)
  - **Disseminate** work to the public in a transparent way (design reports, public TEA tools)

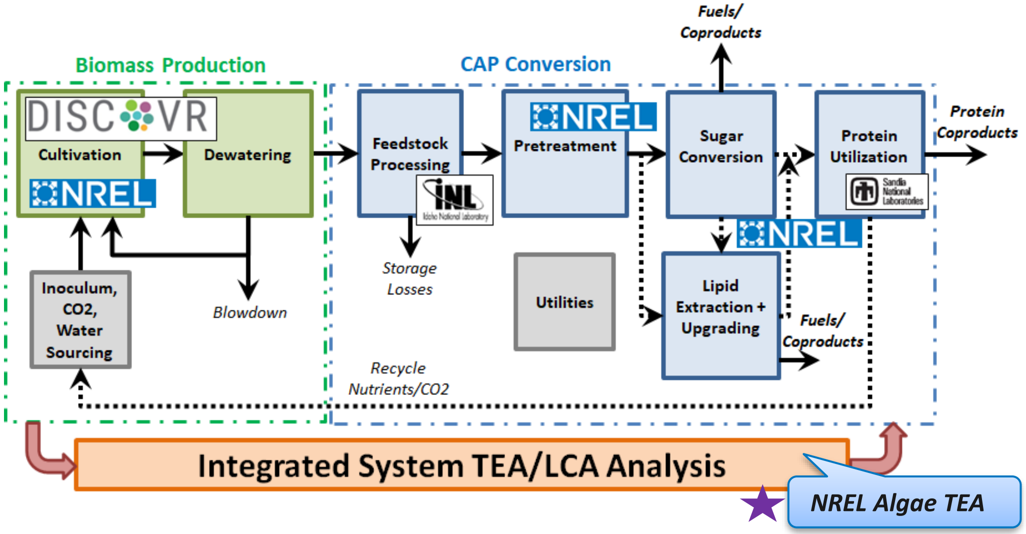
Context:

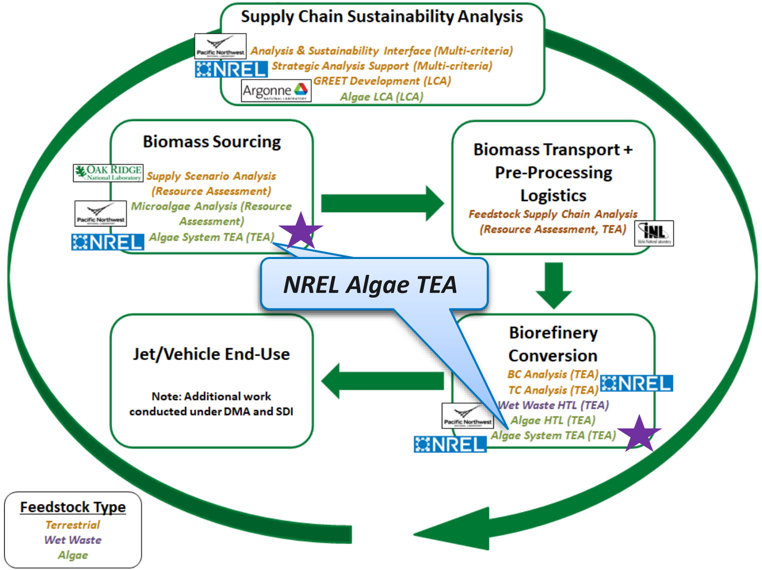
- This project provides **direction, focus, and support** for industry and BETO by providing "bottom-up" TEA to show R&D needs for achieving "top-down" BETO goals (e.g. *3B gal SAF + 50% GHG reduction by 2030, 35B gal SAF by 2050*)
- One of the longest-serving projects under BETO Algae Platform – 13-year history of impactful, authoritative TEA on algae systems

1. Approach

- **Highly integrated with R&D efforts** – proactive assistance in R&D planning
- Substantial collaboration with NREL researchers, consortia partners spanning the value chain
- Dual focus covering both cultivation + conversion research = *"how to optimize"* biomass production and *"what to do"* with it

- **Strong collaboration with other analysis projects** – harmonize analysis for bigger picture
- Monthly calls to update other analysis projects, exchange information, plan milestones
- Currently completing a multi-lab "algae harmonization" update (joint with ANL/PNNL)
  - Includes review/vetting step with industry experts

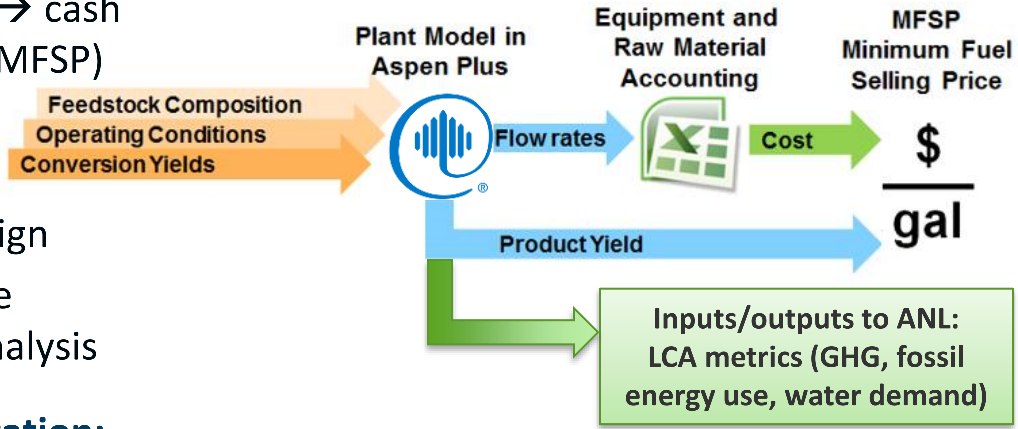




1. Approach

Technical Approach:

- Aspen Plus modeling for rigorous M&E balances → cash flow calculations set minimum fuel selling price (MFSP)
- Credibility of analysis supported by expert consultants, vetting with external stakeholders
- Highlight drivers/risks/challenges vs baseline design
- Measure progress through annual SOTs, prioritize future **R&D "bang for the buck"** via sensitivity analysis



Risks/Challenges:

- Risk: TEA/LCA optimized for a single productivity + composition target
- Risk: Focusing only on hypothetical future algae farms, missing opportunity to support today's algae industry
- Challenge: Specific MFSP targets require complex biorefinery configurations – commercial relevance?

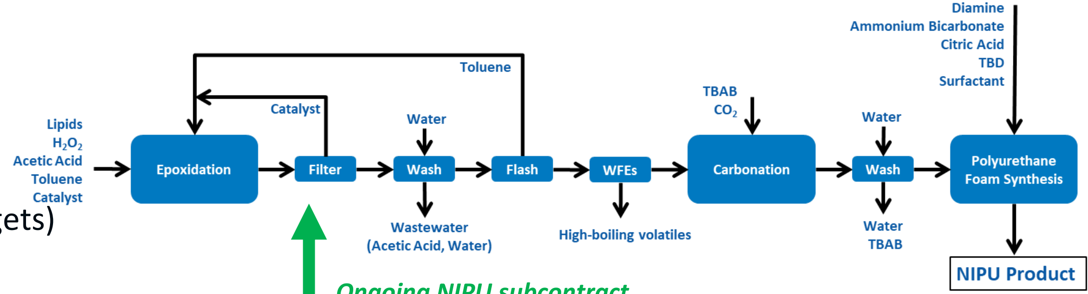
Mitigation:

- Iterate with R&D projects to evaluate cost vs composition tradeoffs, establish multiple goal case scenarios
- Include analysis for today's algae resources (WWT, algal blooms, etc.), how to best utilize them at local scale
- BETO *moving away from specific MFSP targets*; future design cases will prioritize scale-up practicality and current industry drivers

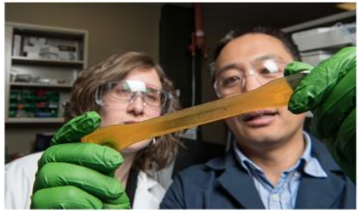
1. Approach

Management Approach:

- Approach is guided by milestones:
  - TEA/LCA support for R&D projects
  - Refine/improve our tools and capabilities
  - Guidance for overall Algae Platform (out-year targets)
- Staffing: emphasis on process engineering expertise
  - 3+ process engineers on project
  - Work with engineering subcontractors to improve model fidelity
- FY23 key focus on **more engagement from/relevance to industry**
  - **Go/No-Go decision** (FY23 Q2) on whether/how to incorporate policy incentives into TEA metrics – key industry driver
  - Close tie-ins with DISCOVR → incorporate learnings from TAB guidance to refine model details (e.g. salinity handling)

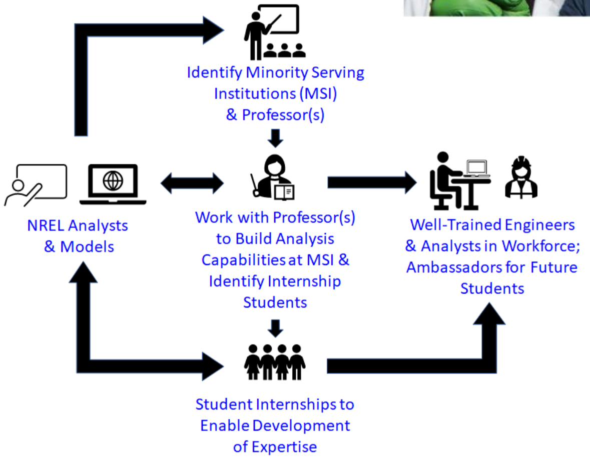


Ongoing NIPU subcontract with engineering firm – improve model fidelity for pre-commercial technology



Diversity, Equity, and Inclusion:

- DEI goals established by pooling resources in TEA group (includes Algae TEA, BC Analysis, TC Analysis, Strategic Support)
- Goal: Establish working relationship with MSI university, help them develop TEA/LCA capabilities
  - FY25 DEI milestone: Joint TEA/LCA manuscript with MSI collaborator
- Democratizing access to analysis (public TEA models, reports)

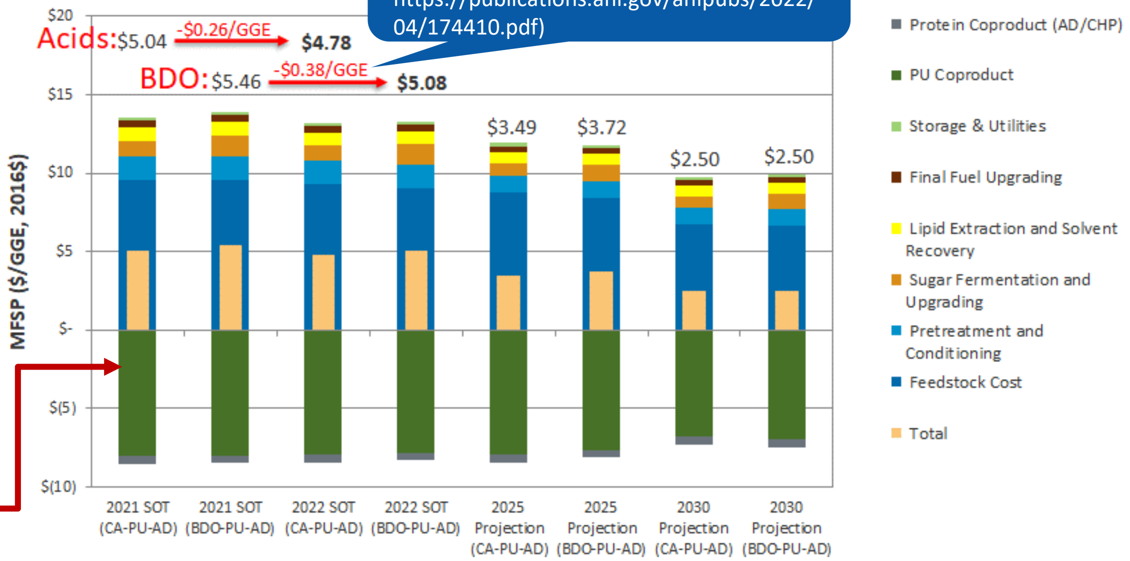


2. Progress and Outcomes

NREL TEA Sets SOT Benchmarks

- Incorporated cultivation data from DISCOVR partners to support SOT
- Continued experimental progress demonstrated across FY21-22 trials:
  - FY21 experienced a summer drop-off, likely due to summer weather pattern
  - Recovered in FY22 to achieve **best overall productivity to date** – driven by *P. celeri* + *T. striata* seasonal rotations
- Further reduced CAP conversion MFSPs by ~$0.3-$0.4/GGE via improved fermentation
  - **MFSPs driven strongly by inclusion of PU coproduct from lipids**

~5% GHG reduction vs 2021 SOT, similar GHG for acids case (ANL SCSA: https://publications.anl.gov/anlpubs/2022/04/174410.pdf)



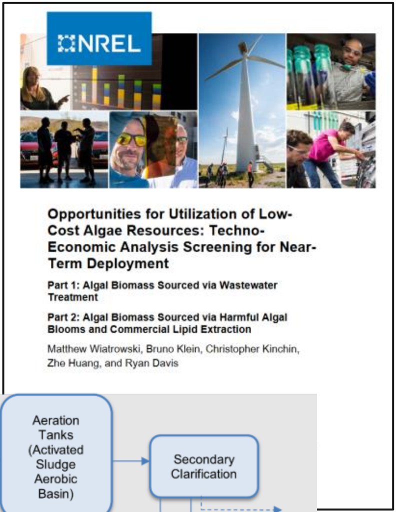
Productivity (g/m²-day)	2015 SOT (ATP³)	2016 SOT (ATP³)	2016 SOT (ABY1 Performer)	2017 SOT (ATP³)	2018 SOT (ATP³/ DISCOVR/ RACER)	2019 SOT (DISCOVR)	2020 SOT (DISCOVR)	2021 SOT (DISCOVR)	2022 SOT (DISCOVR)	2030 Projection
Summer	10.9	13.3	17.5	14.1	15.4	27.1	31.6	23.8	29.0	35.0
Spring	11.4	11.1	13.0	13.2	15.2	18.6	18.5	19.4	19.9	28.5
Fall	6.8	7.0	7.8	8.5	8.5	11.4	15.0	19.1	16.2	24.9
Winter	5.0	5.0	4.8	5.5	7.7	6.4	8.3	8.3	9.0	11.7
Average	**8.5**	**9.1**	**10.7**	**10.3**	**11.7**	**15.9**	**18.4**	**17.6**	**18.5**	**25**
Max variability	**2.3:1**	**2.7:1**	**3.6:1**	**2.6:1**	**2.0:1**	**4.2:1**	**3.8:1**	**2.9:1**	**3.2:1**	**3.0:1**
MBSP ($/ton, 2016$)	**$1,142**	**$1,089**	**$960**	**$909**	**$824**	**$670**	**$603**	**$611**	**$602**	**$488**

- *Maintained comparable performance since 2020 SOT*
- *7-year progression: **47% MBSP reduction, 2.2X productivity increase** since SOT began FY15*

2. Progress and Outcomes

TEA Highlights Near-Term Opportunities for Waste Algae Resources

- **Longer-term:** *potential for 200MM ton/yr* algal biomass (*15+ BGGE/yr* algal fuel) via "farmed" algae – BUT requires high CAPEX investment ($800MM for integrated system), >$5/GGE coproduct credits
- **Near-term:** potential for smaller-scale industry opportunities leveraging "waste" algal biomass sources (much lower cost)
- Tech report published September 2021, evaluating:
  - Volume 1: Wastewater treatment (WWT)
  - Volume 2: Harmful algal blooms (HABs) + residual biomass from current industry extraction operations (EXT) for ω-3's
- Structured around *near-term deployment at small distributed community-scale* → highlight opportunities to expand the algae industry in coming years without high-CAPEX farming
  - Environmental equity tie-ins, e.g. HAB impacts on local communities and economies



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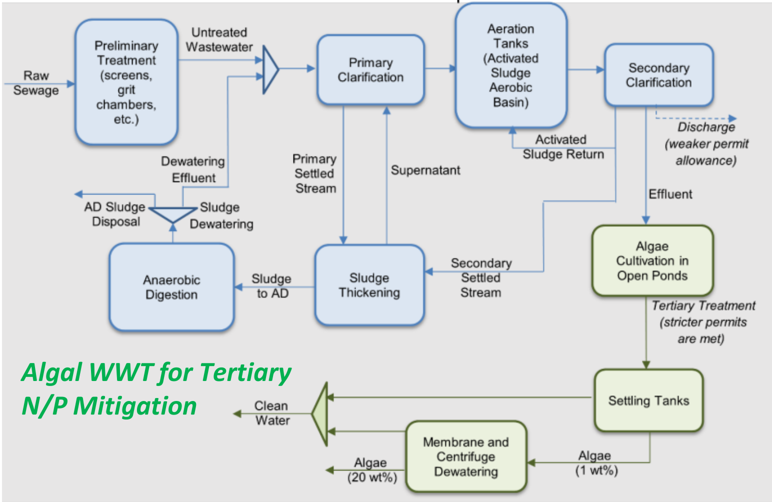
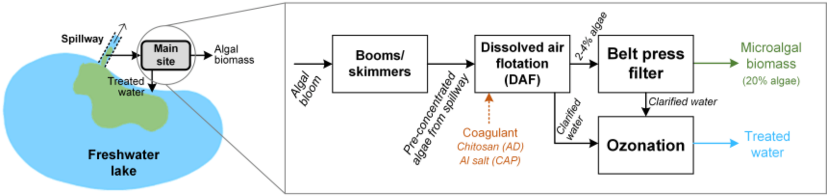


Algal WWT for Tertiary N/P Mitigation



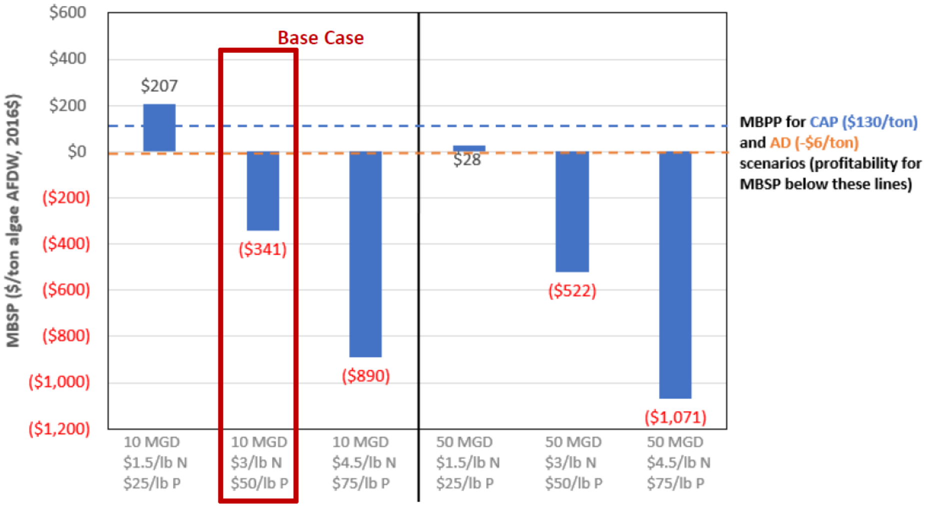
Algal Bloom Biomass Collection

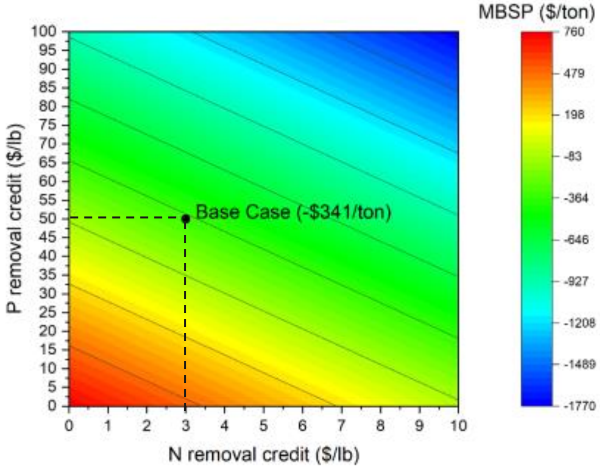
2. Progress and Outcomes

Algal WWT: Strong Economic Potential for Biomass Production + Conversion

- Very good potential for economic viability at base case conditions
- Negative MBSPs imply facility could (theoretically) *pay* up to $341/ton for biomass disposal
- Downstream conversion can accommodate a max. biomass purchase price (MBPP) up to $130/ton (CAP) or -$6/ton (AD)
- Economics improve for larger WWT scale, higher N/P treatment credits

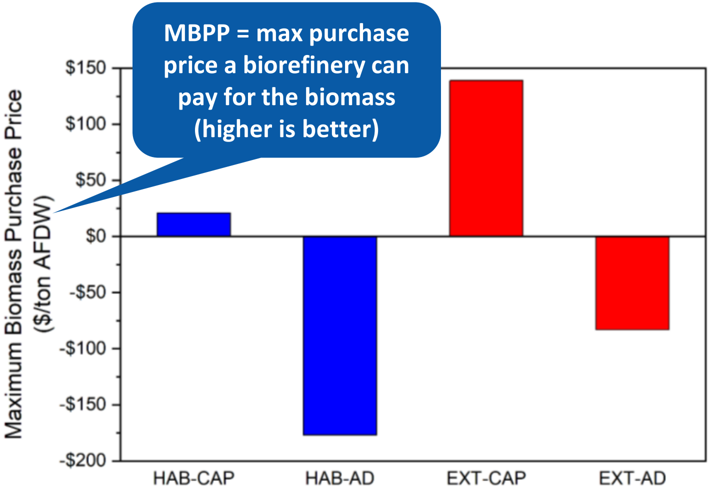
- Nutrient credits significantly influence process economics
- Particularly driven by P treatment credits
  - Keep P credit only: –$98/ton MBSP
  - Keep N credit only: $512/ton MBSP
- Indicates that localities with stricter P discharge limits could be logical early adaptors of algal WWT



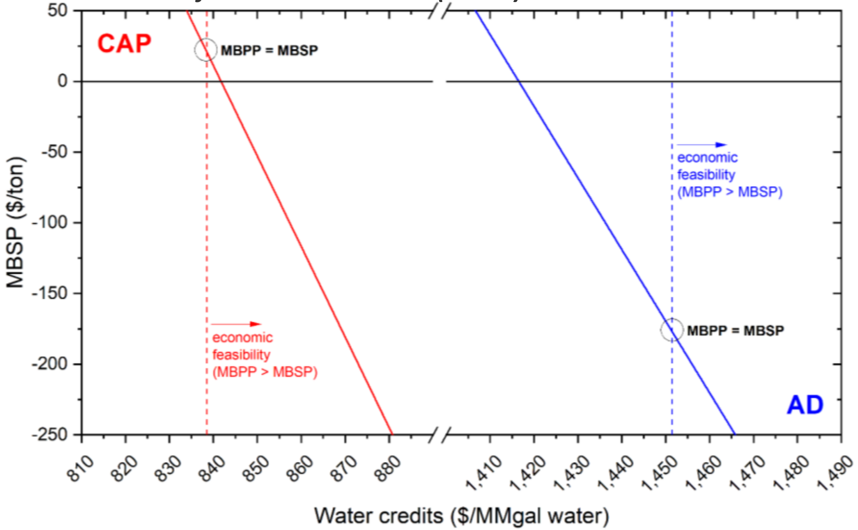


2. Progress and Outcomes

Opportunities Also Exist for Conversion of Harmful Algal Blooms + Commercial Extracted Algae



HAB: Cost of Biomass Collection (MBSP) vs Water Treatment Credit



- EXT biomass somewhat more economical than HAB due to intermittent HAB availability (seasonal processing)
- CAP conversion of HAB/EXT biomass (carbs to ethanol, residual solids to bioplastics) reflects better economics vs AD
- But, AD can considerably improve with inclusion of RNG policy credits

- Though a rough "feasibility-level" analysis, results can be used to estimate required water treatment credits
- HAB economics for biomass collection are strongly dependent on value of water remediation credits (paid by local governments)
- Required water credits to achieve viability for conversion vary between $828/MMgal (CAP) and $1,451/MMgal (AD)

2. Progress and Outcomes

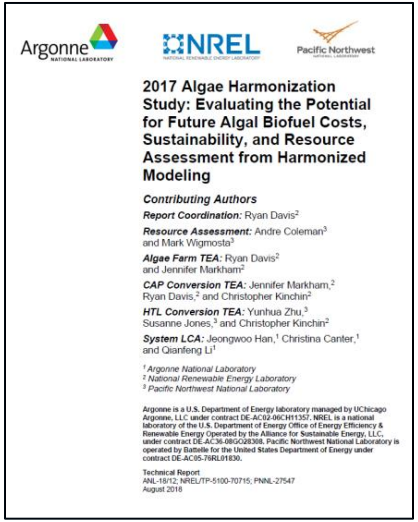
BETO Reconvenes Lab Partners for Updated Algae Harmonization Study

2017 Harmonization Study:

- Focused on longer-term future potential (5,000 acre farms, low-protein biomass)
- Included focus on high-value chemical coproducts
- Highlighted potential for up to 250 MM ton/year biomass via CCU integration (saline cultivation)
- Translated to 8+ BGGE/yr fuel potential depending on coproduct constraints

2022 Harmonization Update:

- Focused on near-term deployment potential (1,000 acre farms, high-protein biomass)
- Focus on fuels (SAF) + protein for food/feed markets
- More refined approach for CO_2 sourcing/transport (still CCU) and saline blowdown management
- Driven by LCA to prioritize fuel pathway design selections


Argonne NATIONAL LABORATORY
NREL NATIONAL RENEWABLE ENERGY LABORATORY
Pacific Northwest NATIONAL LABORATORY

2017 Algae Harmonization Study: Evaluating the Potential for Future Algal Biofuel Costs, Sustainability, and Resource Assessment from Harmonized Modeling

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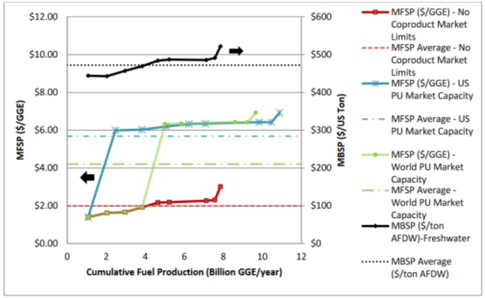
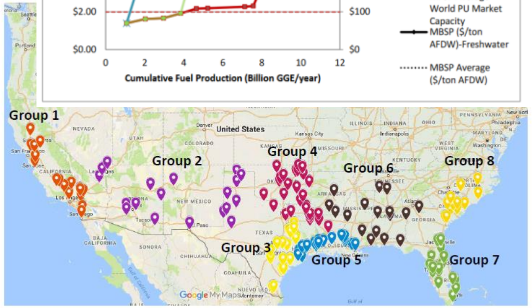
Technical Report
ANL-18/12; NREL/TP-5100-70715; PNNL-27547
August 2018





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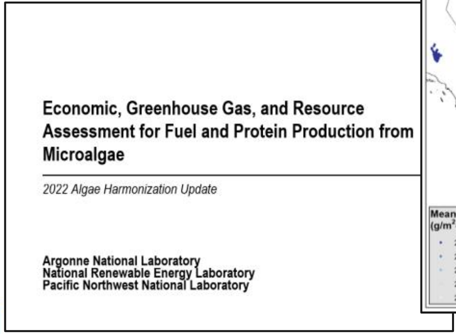
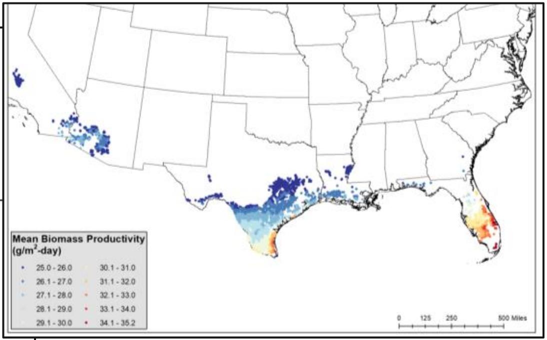
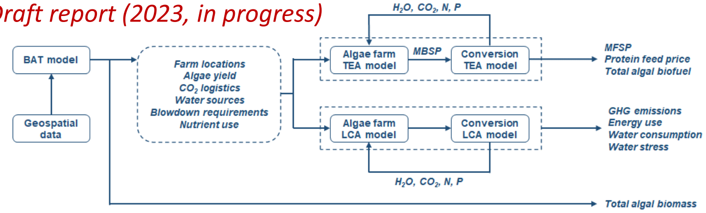

Economic, Greenhouse Gas, and Resource Assessment for Fuel and Protein Production from Microalgae

2022 Algae Harmonization Update

Argonne National Laboratory
National Renewable Energy Laboratory
Pacific Northwest National Laboratory



Draft report (2023, in progress)

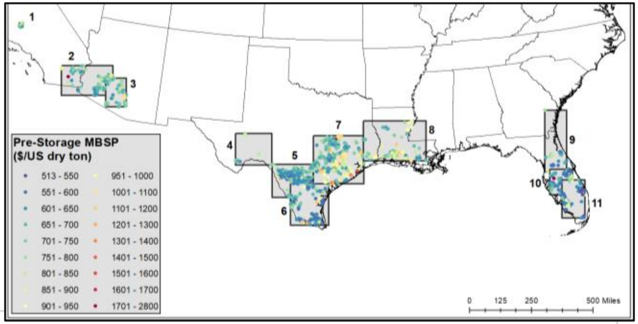


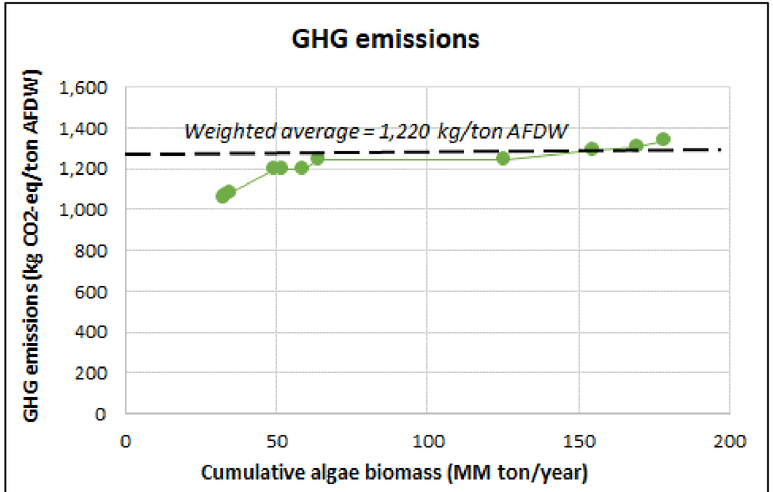
2. Progress and Outcomes

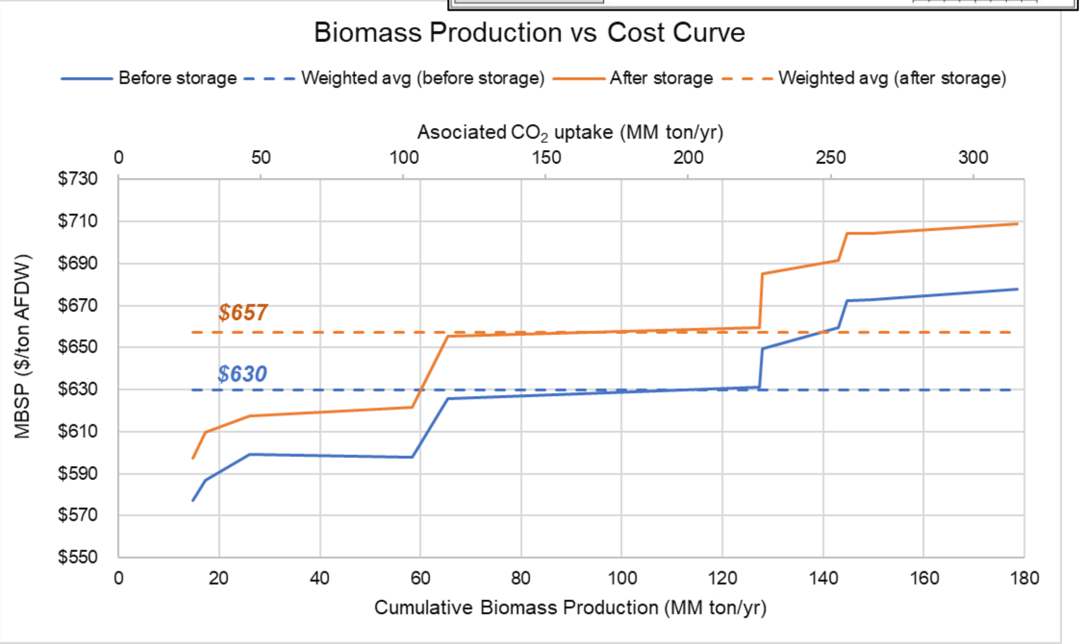
Preliminary Results: 2022 Harmonization update

- Overall slightly lower total biomass potential (~180 MM vs 250 MM ton/yr) relative to 2017 harmonization
- But, similar cumulative avg. cost (MBSP)
- High salinity strains @ 50ppt limit excessive blowdown handling costs
  - Disposal via deep-well injection (ocean disposal possible for some coastal sites, but not included here)
- GHG emissions driven more strongly by CCU sourcing details

Draft results, not yet finalized



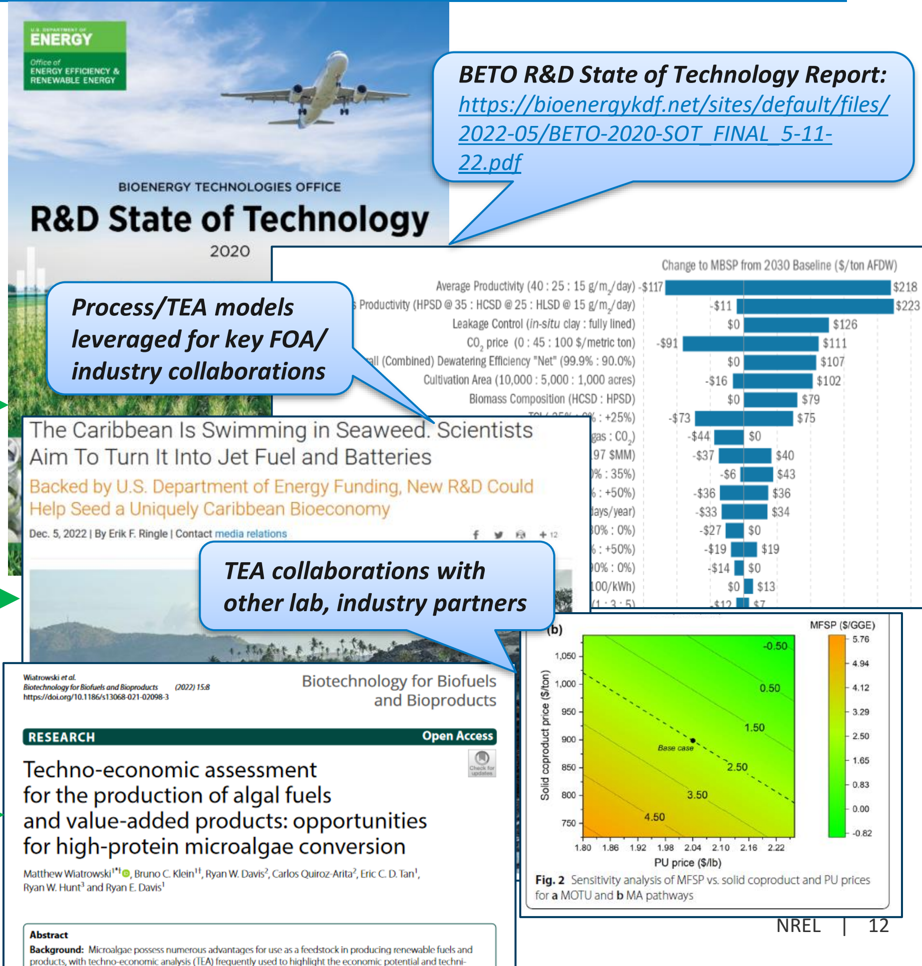




3. Impact

Algae TEA project provides high impact:

- Dissemination of information to the community:
  - **Over 30,000 downloads** of algae TEA reports, 350+ downloads of TEA models in the **past 3 years** (https://www.nrel.gov/extranet/biorefinery/aspen-models/)
- Leverage framework set by this project to support a wide variety of stakeholders:
  - Research community, decision makers
  - **Guide R&D/DOE decisions to set targets**
  - Direct collaboration/participation with consortia
  - FOA partnerships (>5) + industry collaborations
- **Foster collaboration** with other modeling/research groups while **increasing interactions with industry**
  - Recent analysis joint with SNL, Algix: high-protein conversion opportunities for CAP processing
  - Future work: incorporate feedback from 5 industry expert reviews for harmonization report, further engage with industry to guide FY24 design case update

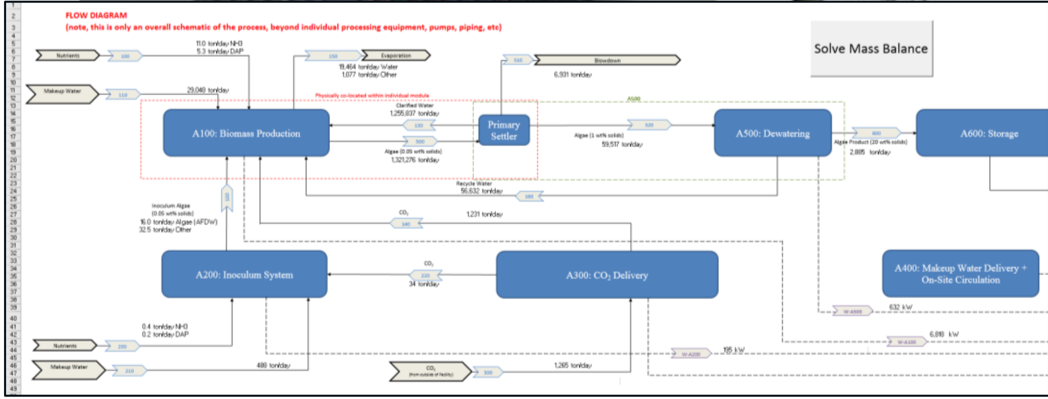


Summary

Algae System TEA Project Provides Crucial Bridge From Technology R&D To Economics + Sustainability

Summary

- **Management:** Strong team with **extensive collaboration** across BETO R&D portfolio + BETO analysis projects
- **Approach:** Continuous iteration of TEA concepts to **maximize efficiency of R&D dollars, de-risk** technology pathways
- **Impact:** High impact via **external engagement** (industry, research/consortia collaborators), focus on **transparent dissemination** of work
- **Outcomes:** Work is key to supporting BETO mission by **highlighting requirements to achieve economic + sustainability goals**, prioritize future research directions
- **Future Work:** Select example CAP conversion pathways **tailored to biomass cost/composition scenarios** via SAF/coproduct focus (FY23 milestone) → Publish updated design report for selected pathways (FY24 milestone)



Algae farm TEA spreadsheet tool: https://www.nrel.gov/extranet/biorefinery/aspen-models/

Quad Chart Overview

Timeline

- Project start date: Oct 1, 2021 (3-year cycle)
- Project end date: Sept 30, 2024 (3-year cycle)

	FY22 Costed	Total Award
DOE Funding	$375,000 (FY22 BA)	$1,075,000 (FY22-FY24)
Project Cost Share	N/A	N/A

TRL at Project Start: 3-5*
TRL at Project End: 4-6*
**TRL is N/A (Modality #5: strategic, market, and techno-economic analysis)*

Project Goal

Provide techno-economic modeling and analysis to *quantify economic impact* of algae program R&D activities. This is done through creation of *process/TEA models* for cultivation, processing, and conversion of algal biomass to fuels and co-products (CAP conversion), *relating key process parameters with overall economics and providing key outputs to quantify GHG emissions relative to BETO goals*.

End of Project Milestone

Deliver algae CAP design report update – draft for publication (FY24 Q4): Submit a final draft for publication approval of an *updated CAP Design Report*. Report will incorporate feedback from review of first draft, and will *document technical and TEA/LCA targets* reflective of the latest NREL research and TEA model refinements for *achieving BETO goals for ≥70% GHG reduction at reasonable cost* focused on production of algae-derived SAF and/or products. Report *will guide future experimental plans* for CAP pathway focus *based on key cost/GHG drivers*.

Funding Mechanism

FY22 AOP Lab Call (Algae)

Project Partners

No partners with shared funding (but collaborate frequently with other algae analysis projects at ANL, PNNL, ORNL, INL, SNL, plus DISCOVR)

Acknowledgements:

- Matt Wiatrowski
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- DISCOVR consortium

Thank you!
Questions?

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NREL Transforming ENERGY

Acronyms

- AD = anaerobic digestion
- AFDW = ash free dry weight
- BDO = 2,3-butanediol
- CA = carboxylic acids
- CAP = Combined Algae Processing (biochemical algae conversion process)
- CCU = carbon capture and utilization
- Design case = future technical target projections to achieve TEA cost goals
- GGE = gallon gasoline equivalent
- HAB = harmful algal blooms
- MBSP = minimum biomass selling price
- MFSP = minimum fuel selling price
- MOT = mild oxidative treatment
- NIPU = non-isocyanate polyurethanes
- PU = polyurethanes
- SAF = sustainable aviation fuel
- SOT = state-of-technology (annual benchmarking to update TEA based on latest R&D data)
- TEA = techno-economic analysis
- WWT = wastewater treatment

Additional Slides

Responses to Previous Reviewers' Comments

- The opportunities to piggy back on [WWT] infrastructure and systems with little to no additional investment to accommodate algae as well as the abundance of existing nutrients and source water simply never lose their appeal. Most previous attempts achieve limited success for a variety of reasons. The possible risks do not seem reflected or otherwise addressed in the project.
- We thank the reviewers for their insightful comments, and appreciate the recognition of the merits of this project in guiding NREL/BETO program directions. In response to the comment noting the potential to miss key risks in the deployment of algal systems for wastewater treatment, we have held numerous discussions with two large industry players in the algal WWT space to better understand such constraints and realistic gaps/drivers in the implementation of this concept at scale, in hopes to incorporate further inputs and refine our modeling activities on the topic. Those additional efforts have now translated to updating our algal WWT models in further granularity as part of our recently-published "waste algal resources" report (https://www.nrel.gov/docs/fy22osti/81780.pdf).

- Goals are clearly stated and the risk management strategy is clear; however, it would have been helpful to see more detail on roles and responsibilities, communication methods and data sharing.
- On the comment of project interactions and data sharing, this project interacts frequently with both internal and external partners including consortia groups, FOA partners, national laboratory modelers, and industry collaborators to foster information exchange. This includes communicating data input needs, working with researchers to collect this data (often iterating several times to translate the data into the most suitable format for incorporation into the models), and sharing outputs of the TEA models to highlight key drivers and priorities versus inconsequential factors not worth experimental focus. For example, we communicate on a weekly basis with the DISCOVR consortium to communicate ongoing data needs for cultivation trials, and have led many of the discussions with the Technical Advisory Board under that consortium based on model inputs and subsequent findings. Likewise, we communicate at least several times per month with NREL algae CAP conversion researchers to guide progress, provide TEA insights to down-select across competing research priorities, and revisit the latest performance data for use in SOT benchmarking updates.

Publications, Patents, Presentations, Awards, and Commercialization

Publications/Reports (since 2021 review):

- M. Wiatrowski, B. Klein, C. Kinchin, Z. Huang, R. Davis. "Opportunities for Utilization of Low-Cost Algae Resources: Techno-Economic Analysis Screening for Near-Term Deployment." NREL/TP-5100-81780. September 2022. https://www.nrel.gov/docs/fy22osti/81780.pdf
- J. Clippinger, R. Davis, "Techno-economic assessment for opportunities to integrate algae farming with wastewater treatment." NREL/TP-5100-75237. September 2021. https://www.nrel.gov/docs/fy21osti/75237.pdf
- R. Davis, B. Klein, "Algal biomass production via open pond algae farm cultivation: 2020 State of Technology and future research." NREL/TP-5100-79931. May 2021.
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Backup Slides

Further Details: High-Protein Algae Conversion Study

Tradeoffs Identified for High-Protein Algae Processing

- FY21 TEA evaluated two scenarios for high-protein algae conversion
- Lipids → fuel + PU, insoluble protein → plastics, soluble protein/carbs → fuel via:
  - Mild oxidative treatment + upgrading (MOTU)
  - Fermentation to mixed alcohols (MA)
- Both pathways present potential for economic viability, but require high protein valorization $900-$1000/ton

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Biotechnology for Biofuels and Bioproducts

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Techno-economic assessment for the production of algal fuels and value-added products: opportunities for high-protein microalgae conversion

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Abstract

Background: Microalgae possess numerous advantages for use as a feedstock in producing renewable fuels and products, with techno-economic analysis (TEA) frequently used to highlight the economic potential and technical challenges of utilizing this biomass in a biorefinery context. However, many historical TEA studies have focused on the conversion of biomass with elevated levels of carbohydrates and lipids and lower levels of protein, incurring substantial burdens on the ability to achieve high cultivation productivity rates relative to nutrient-replete, high-protein biomass. Given a strong dependence of algal biomass production costs on cultivation productivity, further TEA assessment is needed to understand the economic potential for utilizing potentially lower-cost but lower-quality, high-protein microalgae for biorefinery conversion.

Results: In this work, we conduct rigorous TEA modeling to assess the economic viability of two conceptual technology pathways for processing proteinaceous algae into a suite of fuels and products. One approach, termed mild oxidative treatment and upgrading (MOTU), makes use of a series of thermo-catalytic operations to upgrade solubilized proteins and carbohydrates to hydrocarbon fuels, while another alternative focuses on the biological conversion of those substrates to oxygenated fuels in the form of mixed alcohols (MA). Both pathways rely on the production of polyurethanes from unsaturated fatty acids and valorization of unconverted solids for use as a material for synthesizing bioplastics. The assessment found similar, albeit slightly higher fuel yields and lower costs for the MA pathway, translating to a residual solids selling price of $899/ton for MA versus $1033/ton for MOTU as would be required to support a $2.50/gallon gasoline equivalent (GGE) fuel selling price. A variation of the MA pathway including subsequent upgrading of the mixed alcohols to hydrocarbon fuels (MAU) reflected a required solids selling price of $975/ton.

Conclusion: The slight advantages observed for the MA pathway are partially attributed to a boundary that stops at oxygenated fuels versus fungible drop-in hydrocarbon fuels through a more complex MOTU configuration, with more

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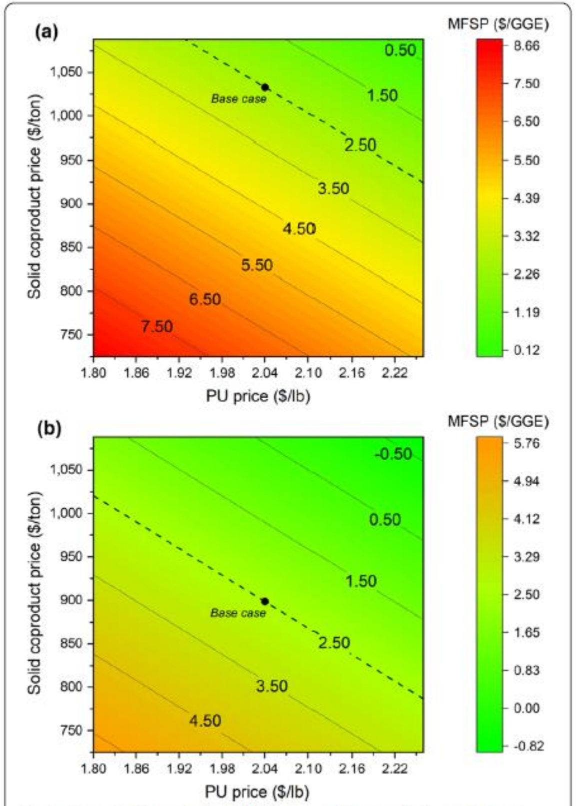
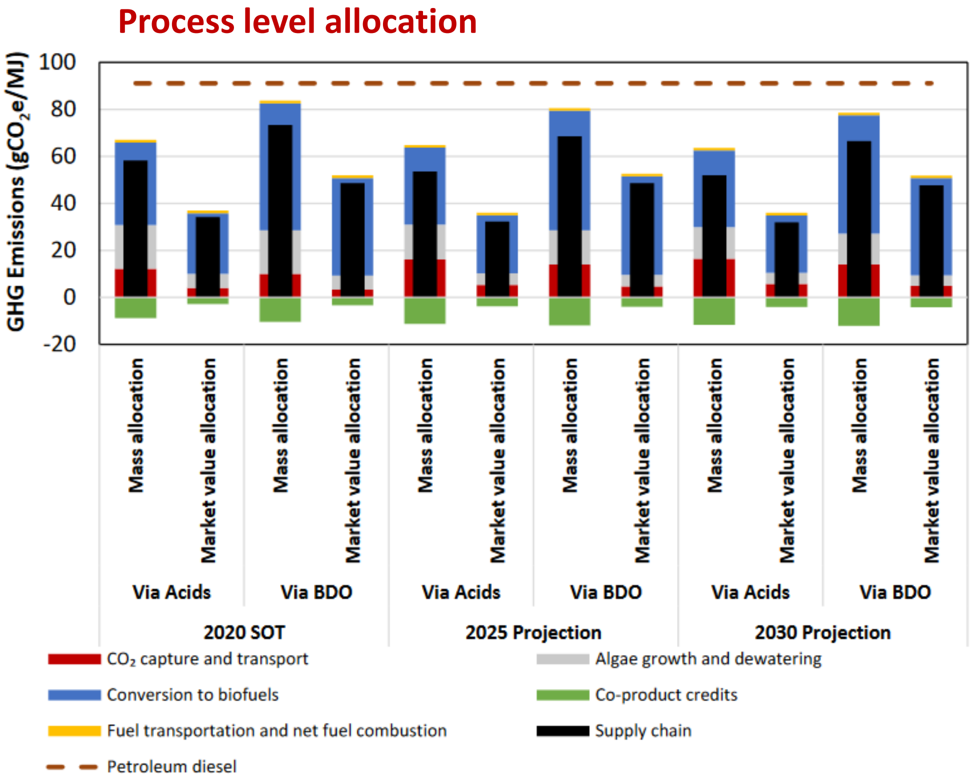


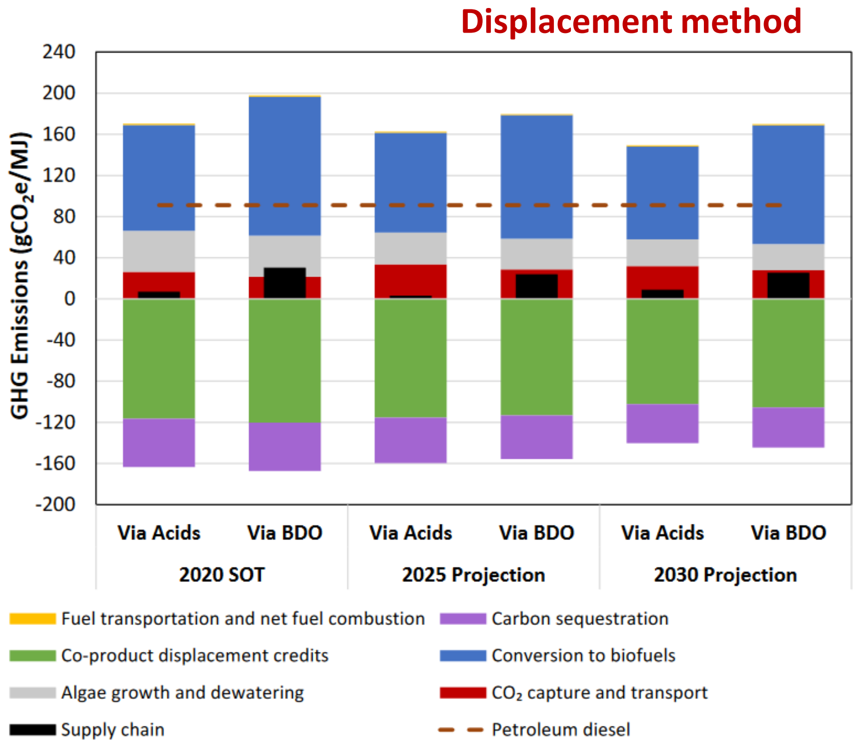
Fig. 2 Sensitivity analysis of MFSP vs. solid coproduct and PU prices for **a** MOTU and **b** MA pathways

Table 1 Key techno-economic metrics of the assessed biorefining pathways

	MOTU	MA
Minimum solid coproduct selling price ($/dry ton) to support $2.5/GGE fuel price	$1033	$899
Fuel yield (GGE/AFDW ton)	34.9	44.6
Fuel yield (MMGGE/yr)	6.6 (0.3 naphtha, 6.3 diesel)	8.4 (6.9 alcohols, 1.5 FAFE)
Fuel C/O molar ratio	n/a (negligible oxygen content)	5.1 (4.6 alcohols, 11.3 FAFE)
Solid coproduct yield (lb/AFDW ton)	1009	1009
Polyurethane coproduct yield (lb/AFDW ton)	254 (140)[a]	254 (140)[a]

Tracking LCA Metrics for SOTs: ANL SCSA Reports





2020 SOT and future out-year cases:
https://greet.es.anl.gov/publication-2020_update_renewable_hc_fuel

Future CAP Design Case Configuration Options

Multiple design cases, optimized based on varying compositional contents of lipids, carbohydrates, and protein