DOE Bioenergy Technologies Office (BETO) 2019 Project Peer Review

1.3.5.200 Algal Biofuels Techno-Economic Analysis

Advanced Algal Systems

March 4, 2019

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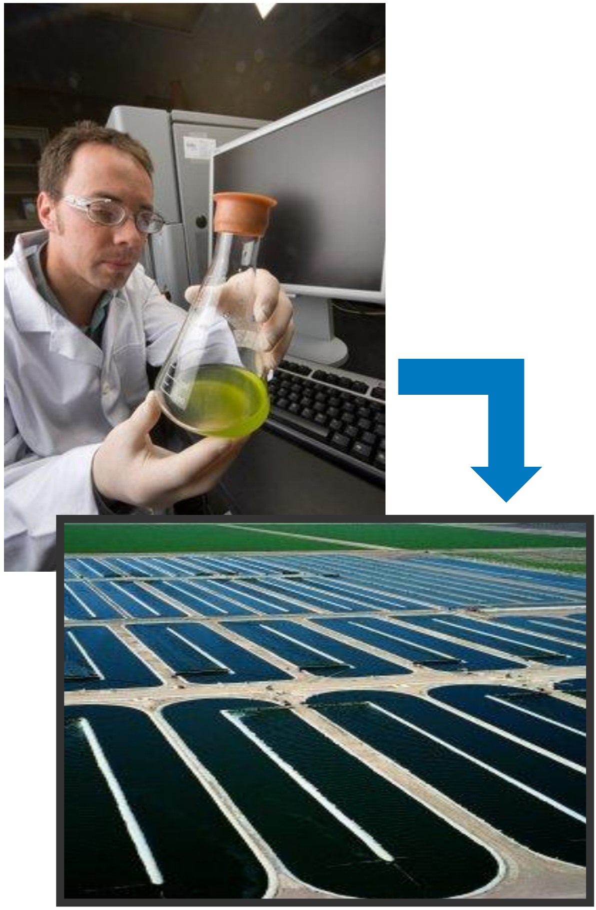
Goal Statement

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
- **Track progress** toward goals through state of technology (SOT) updates
- Conduct **sensitivity analysis** to identify impact of key variables and design alternatives on overall economics
- **Disseminate** rigorous, objective modeling and analysis information in a transparent way (the “design report” process)

Relevance:

•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 cost goals

- Guide R&D toward economic viability, eventual adoption of algal biofuels/products into U.S. market

Quad Chart Overview

Timeline

- Start date: Oct 1, 2010
- End date: Sept 30, 2019 (ongoing, 3-year cycle)
- Percent complete: NA (ongoing AOP project)

Budget

	Total Costs Pre FY17**	FY 17 Costs	FY 18 Costs	Total Planned Funding (FY 19-Project End Date)
DOE Funded	$1.3MM (FY11-16)	$300k	$350k	$350k (FY19)
Project Cost Share*	NA	NA	NA	NA

- **Partners:** No partners with shared funding (but collaborate frequently with other algae modeling projects at ANL, PNNL, ORNL, INL; also interact with ATP3 + DISCOVR consortia)

Barriers addressed

- AFt-A: Biomass Availability and Cost
  - *This project quantifies biomass + fuel costs*
- AFt-H: Integration
  - *TEA models tie all R&D operations together*
- AFt-I: Algal Feedstock On-Farm Preprocessing
  - *Our work strives to optimize processing/ maximize value*

Objective

Provide techno-economic modeling and analysis to support algae program activities. This includes the 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.

End of Project Goal

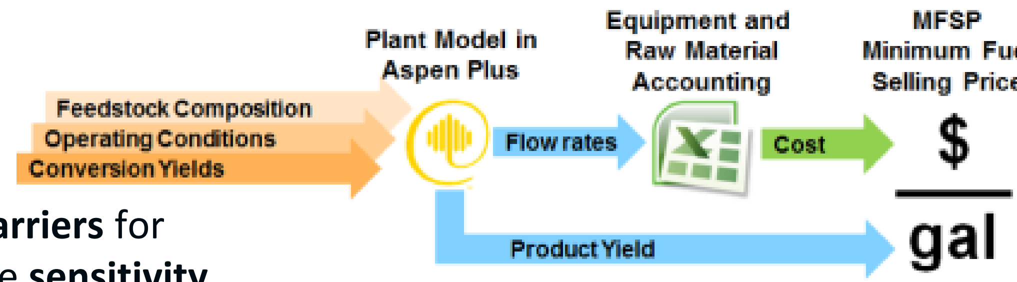
By the end of FY19, deliver new design report to BETO for review and publication approval, focused on algal conversion to fuels and coproducts via the CAP pathway. Design case will focus on optimizing fuel yields while enabling revenues from scalable coproducts and demonstrating market volume capacities, highlighting a path to achieve $2.5/GGE MFSP goals.

Project Overview

- 9-year project history of impactful, authoritative TEA on algal biofuel pathways
  - Commenced in late 2010 to revisit old TEA projections (Benemann, ASP, etc.)
  - Established harmonization models for consistent TEA/LCA/RA in 2012–2013 with ANL, PNNL
  - Design report on novel fractionation process published 2014, biomass cultivation/harvesting published 2016
  - PBR study completed 2016 (paper in preparation)
  - Updated harmonization in 2017 (published 2018)
- TEA models used to set transparent benchmarks, quantify cost impact of funded R&D, highlight cost drivers/hurdles
- Phased approach
  1) Develop baseline models using best available data
  2) Validate and peer review modeling assumptions, publish "design reports"
  3) Assist in cost target development
  4) Iterate with researchers and external stakeholders as new data becomes available to refine models
- Scope of analysis
  - Biomass production/harvesting (→$/ton)
  - Biomass conversion (→$/gal fuels/coproducts)

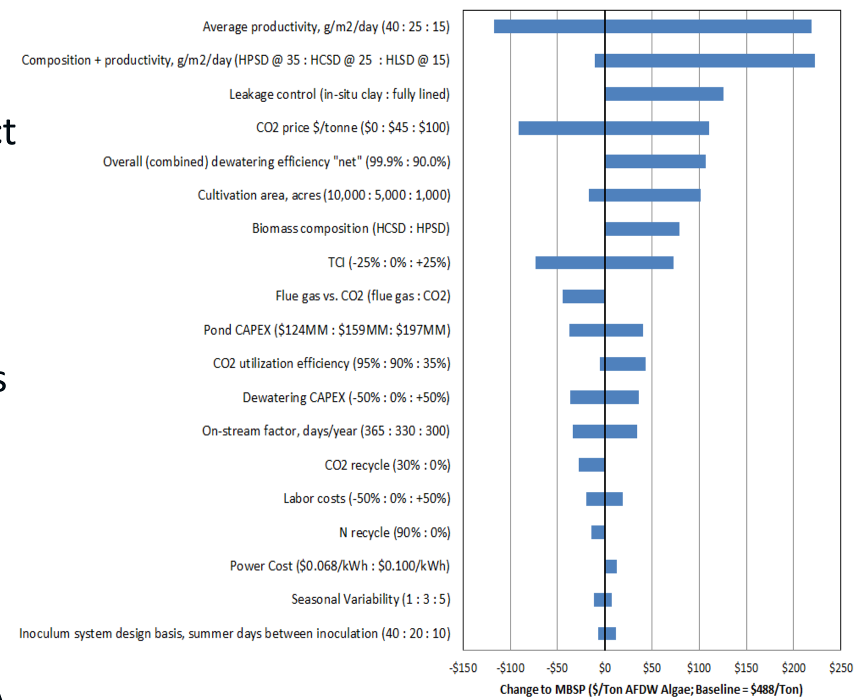
Approach – Technical

- Aspen Plus process models reflect NREL/partner data (preferred), public literature (if necessary)
- Discounted cash-flow calculations determines minimum fuel selling price (MFSP) at fixed IRR
- Credibility of analysis supported by vendor-based cost estimates, thorough vetting with industry and research stakeholders



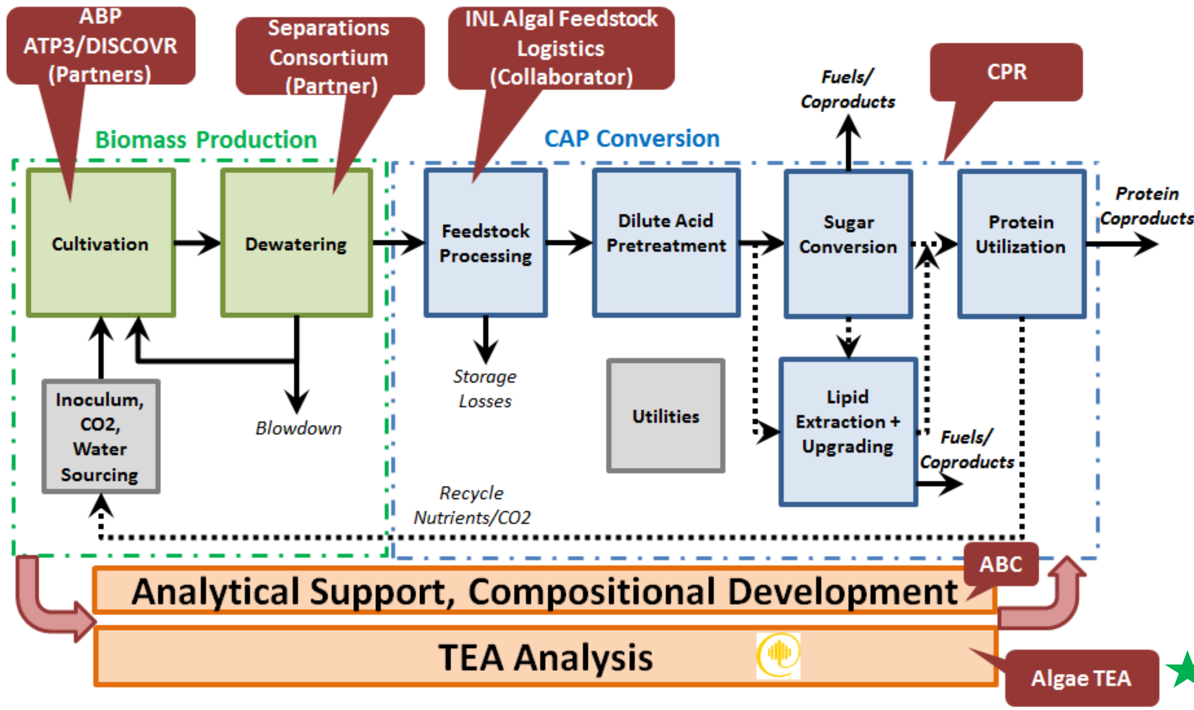
- **Critical success factors:**
  - Process models must be useful: **Highlight barriers** for scale-up in under-researched areas, leverage **sensitivity analysis** to find biggest "bang for the buck" priorities
  - **Maintain credibility** (transparent, unbiased analyses): Engineering subcontracts to reduce uncertainty, subject design reports to thorough external peer review

- **Challenges:**
  - Biomass SOT requires data from long-term growth runs (large-scale, year-round, commercially relevant conditions) – unique challenge for algae SOT vs other platforms
  - Inputs to TEA models are dynamic (material prices, operating conditions, weather influences on annual cultivation performance) – how to capture in static TEA



Approach – Management

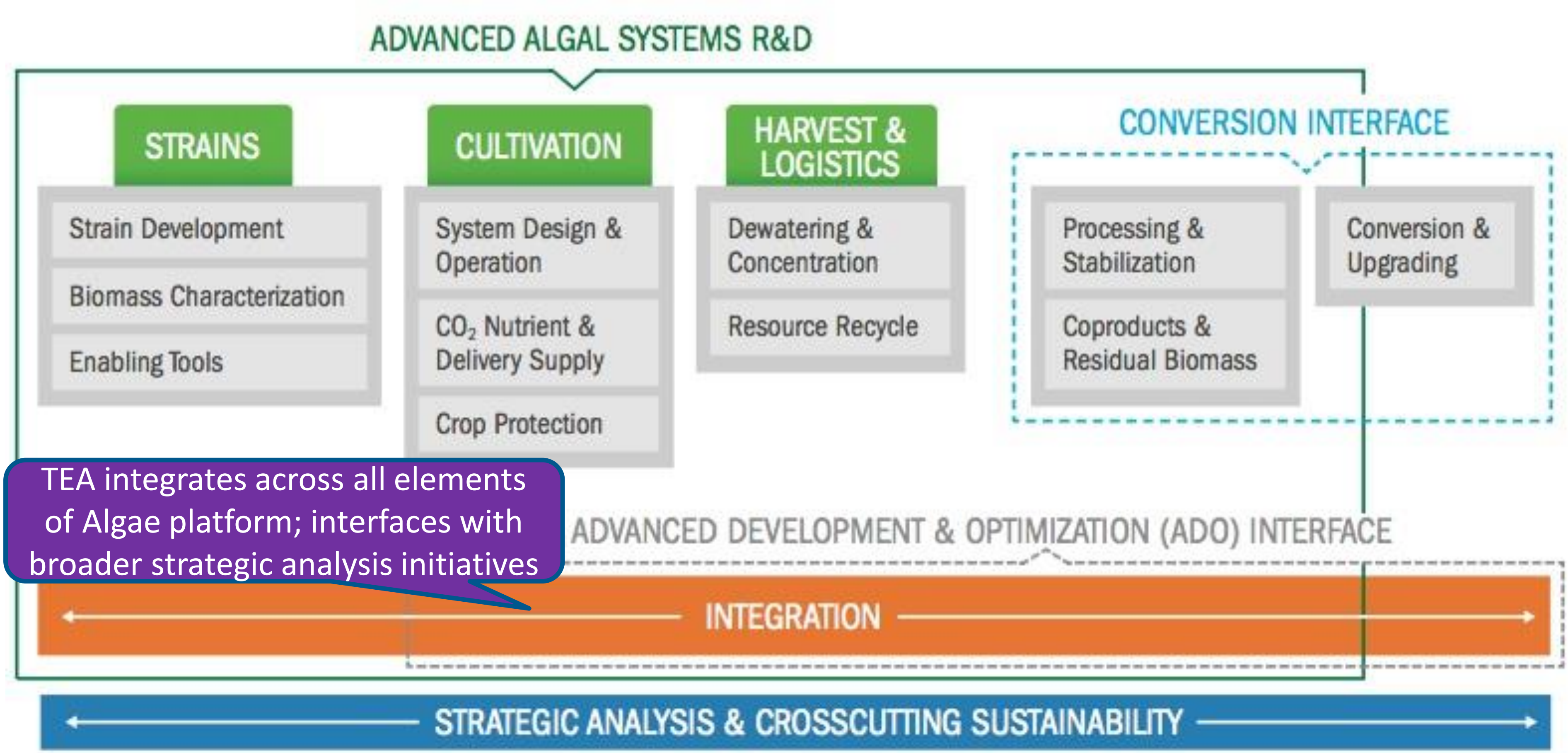
- Project management tracked using milestones
- Monthly platform meetings
- Outreach to external partners + industry – broadening data collection beyond NREL
- Activities highly integrated with research efforts, assist in prioritizations for R&D
  - Example: Using TEA to better understand cost tradeoffs between growth rates vs compositional quality – identify optimum



Project Milestones/Activities	FY17				FY18				FY19 (planned)			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Upstream process focus (biomass production logistics)												
Harmonization modeling (with ANL, PNNL)	▼			▲								
Biomass valorization (growth versus compositional value)		▼								▼		
Algal cultivation for wastewater treatment									▼			
SOT benchmarking					▲			▲				▲
Downstream process focus (biomass conversion to fuels)												
Wet algal biomass storage logistics TEA			▼									
Process/coproduct opportunities for $2.5/GGE algal fuels						▼	⬢					
2019 CAP design report update											▼	▲
SOT benchmarking					▲			▲				▲

▲= Milestone ▼ = Quarterly progress measure ⬢ = Go/no-go decision

Approach – Management: Tie-Ins with Algae Platform



TEA integrates across all elements of Algae platform; interfaces with broader strategic analysis initiatives

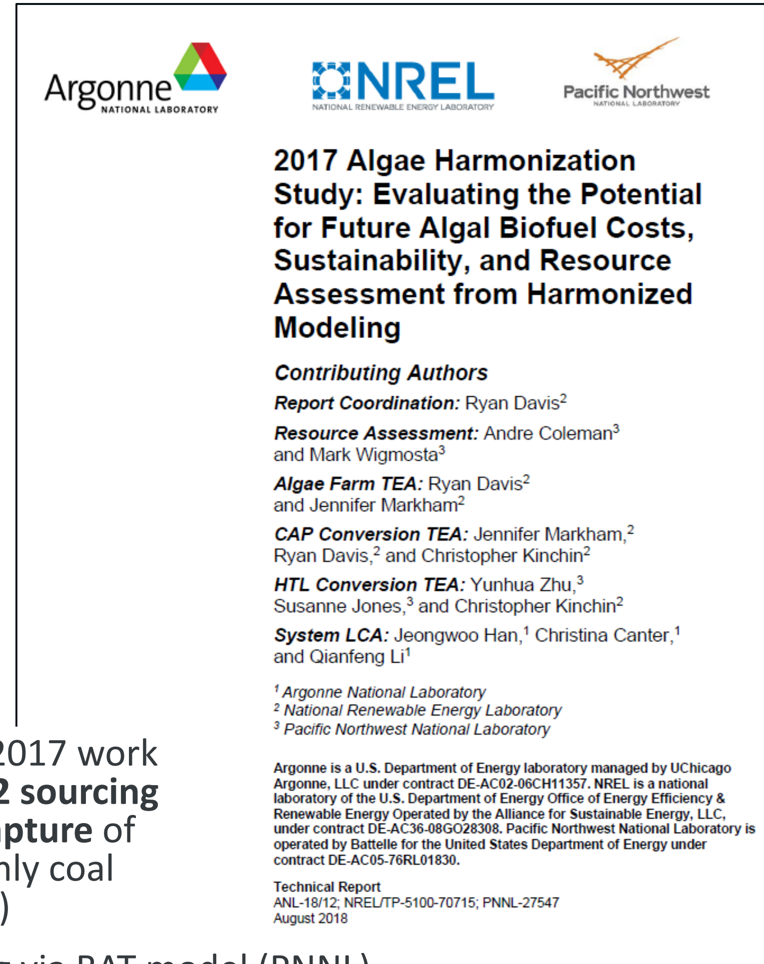
Summary of Key Technical Accomplishments Since 2017 Review

- 2017 Harmonization Report (joint with PNNL/ANL)
- Identification of opportunities for carbon capture
- Highlighting paths to <$2.5/GGE via coproducts
- State of Technology (SOT) benchmarking – reflect R&D data through cultivation + conversion models
- TEA to support biomass valorization framework (identify optima between growth vs composition tradeoffs)

Technical Accomplishments/Progress/Results: *2017 Algae Harmonization Study*

- NREL/ANL/PNNL jointly completed two prior “algae harmonization studies” (2012-2013) focused on harmonized TEA, LCA, and RA
- Prior studies focused on *current technology* ***benchmarks*** with consistent input assumptions
- At BETO’s instruction, harmonization team regrouped in 2017 for a new analysis *focused on* ***future potential***
- Models evaluated national-scale fuel potential for siting algal farms constrained by water and CO_2 availability

https://www.nrel.gov/docs/fy18osti/70715.pdf


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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Argonne is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC under contract DE-AC02-06CH11357. NREL is a national laboratory of the U.S. Department of Energy Office of Energy Efficiency & Renewable Energy Operated by the Alliance for Sustainable Energy, LLC, under contract DE-AC36-08GO28308. Pacific Northwest National Laboratory is operated by Battelle for the United States Department of Energy under contract DE-AC05-76RL01830.

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

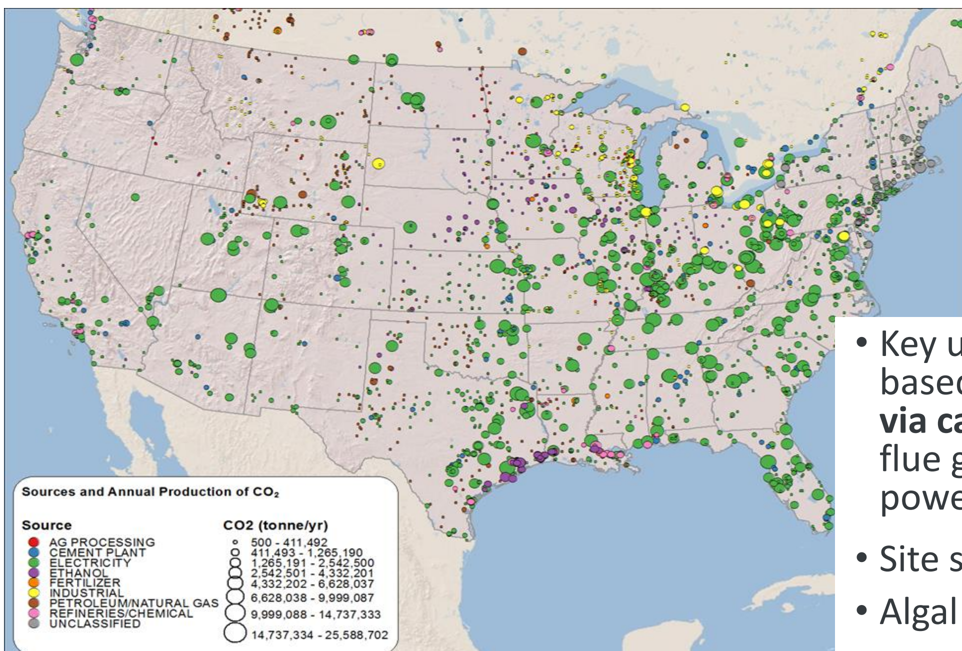


Figure credit, Andre Coleman (PNNL)

- Key update: 2017 work based on **CO2 sourcing via carbon capture** of flue gas (mainly coal power plants)
- Site screening via BAT model (PNNL)
- Algal yields/costs via TEA farm model (NREL)
- TEA of conversion to fuels (NREL/PNNL)
- LCA of fully integrated system (ANL)

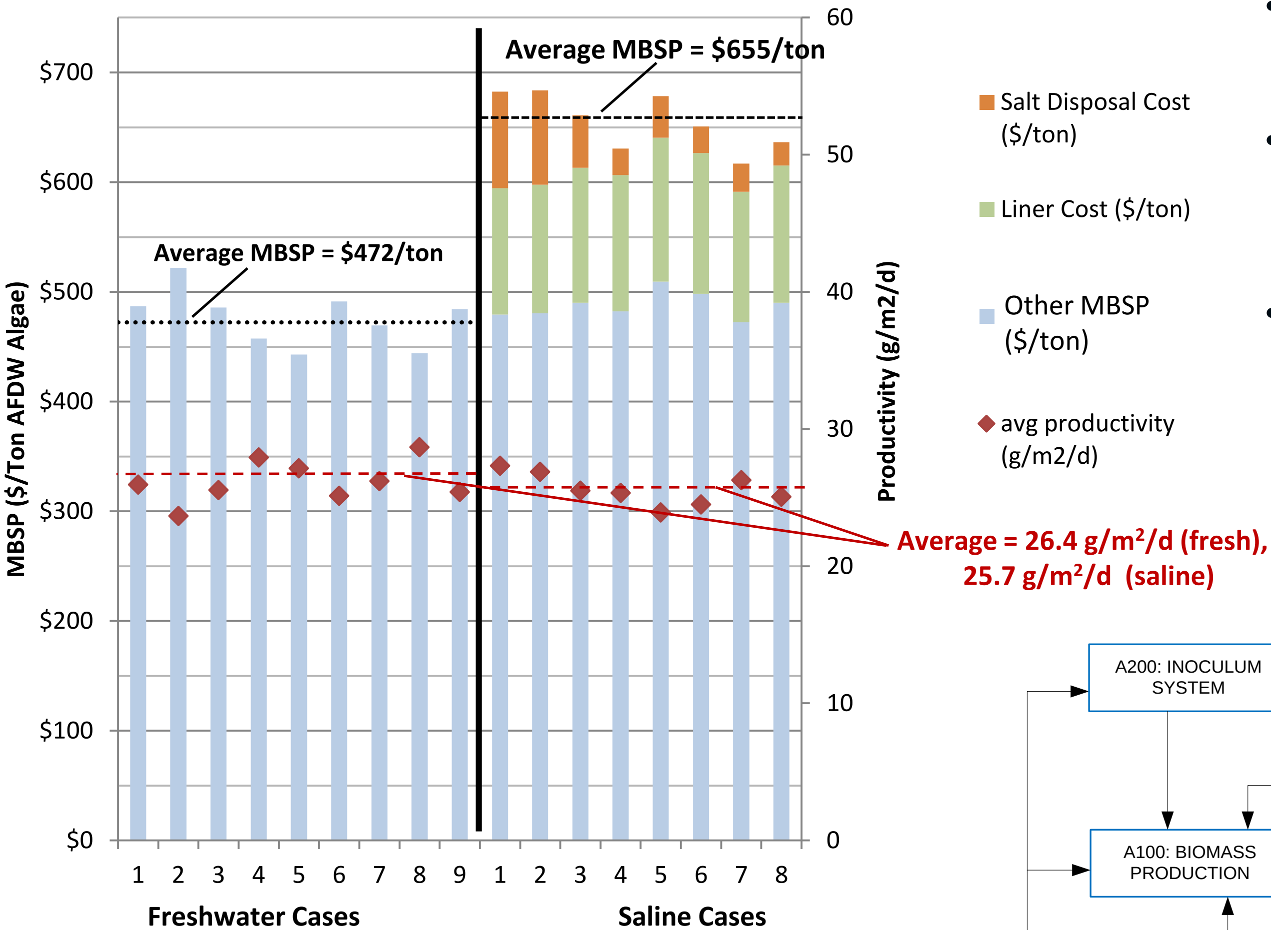
BAT Site Selections – Input to TEA Farm Models

Group Num.	Total Area (Acres)	Number of 5,000-acre Facilities	Productivity ($g/m^2/day$) Annual Average	Winter	Spring	Summer	Fall	Net Pond Evaporation Rate (cm/day) Annual Average	Winter	Spring	Summer	Fall	CO_2 Cost $/tonne (2014$)
1	597,713	119.5	27.31	14.13	35.28	36.67	23.17	0.57	0.11	0.55	1.10	0.54	$43.45
2	1,309,442	261.9	26.87	12.20	34.93	37.59	22.74	0.55	0.18	0.69	0.86	0.46	$41.87
3	859,205	171.8	25.50	15.53	28.16	37.18	21.11	0.26	0.06	0.26	0.51	0.20	$40.96
4	1,322,984	264.6	25.34	15.54	28.33	35.93	21.54	0.10	0.00	0.12	0.18	0.09	$39.76
5	971,459	194.3	23.90	11.45	28.53	36.06	19.57	0.17	0.02	0.12	0.39	0.16	$40.70
6	484,228	96.8	24.50	13.24	28.84	35.36	20.58	0.09	0.00	0.08	0.19	0.10	$41.76
7	995,894	199.2	26.27	16.57	29.36	35.78	23.36	0.11	0.07	0.26	0.07	0.06	$41.14
8	530,148	106.0	25.04	14.34	29.83	35.94	20.06	0.08	0.01	0.13	0.12	0.06	$41.52
Total	**7,071,073**	**1,414**	**25.66**	14.14	30.44	36.41	21.66	**0.25**	0.06	0.30	0.43	0.22	**$41.20**

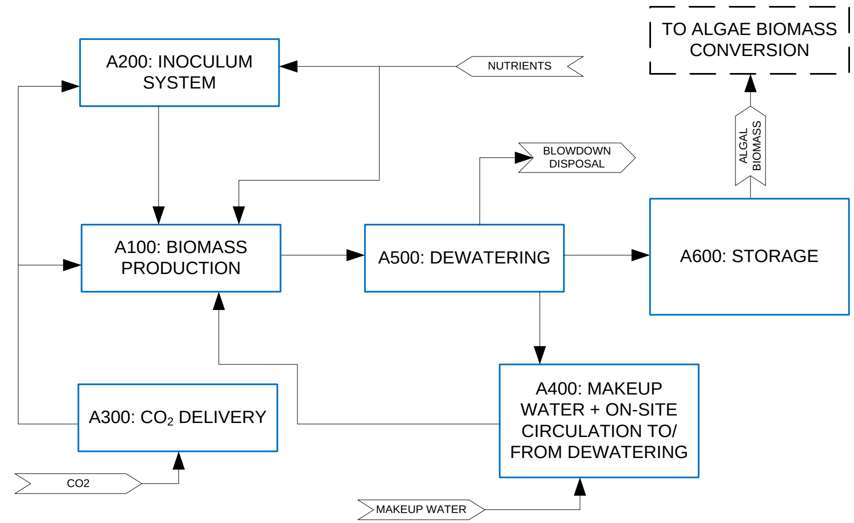
Saline

- RA identified 532 individual farm locations with suitable access to CO2 (via CC) and fresh water (increasing to 1,414 locations when switching to saline water)
- Could enable *up to ~10-27 BGGE/yr of fuels* (@ 25 $g/m^2/day$ + 100 GGE/ton)

Harmonization TEA Farm Results – Biomass Cost (MBSP) Per Site

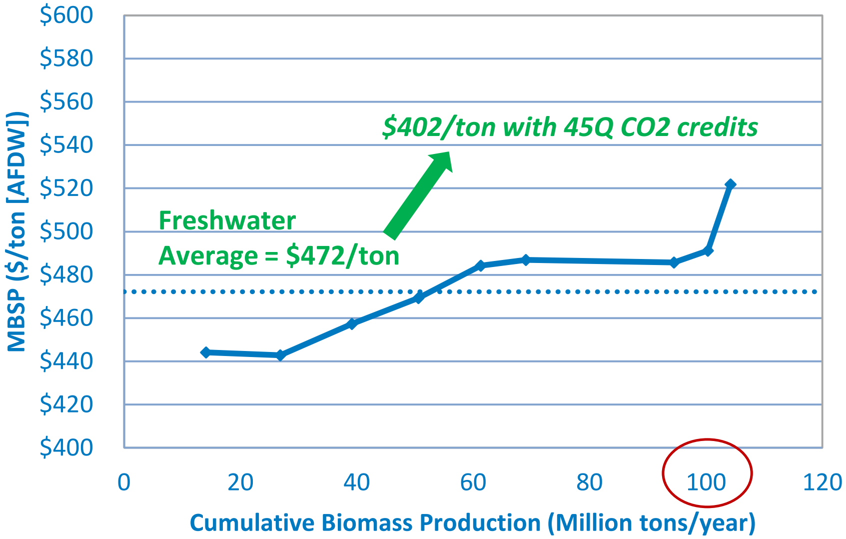


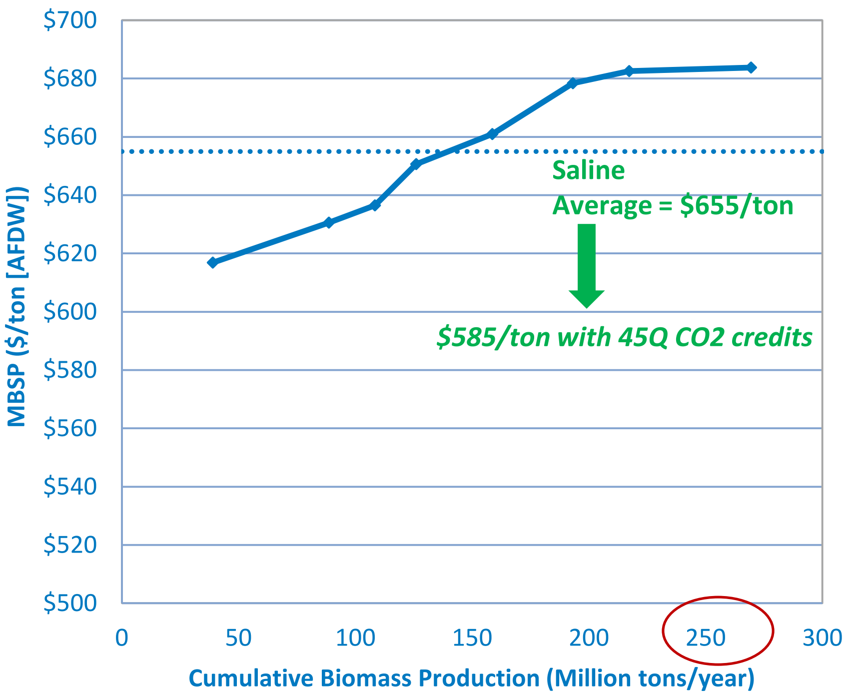
- MBSP is a function of both average productivity + seasonal variability
- Saline adds ~$180/ton (on average) vs freshwater, *“if” liners are universally required*
- *Significant salt disposal costs in arid regions* with high evaporation (California, SW) – must remove more blowdown to maintain salt levels within strain tolerance



NREL algae farm model: https://www.nrel.gov/docs/fy16osti/64772.pdf

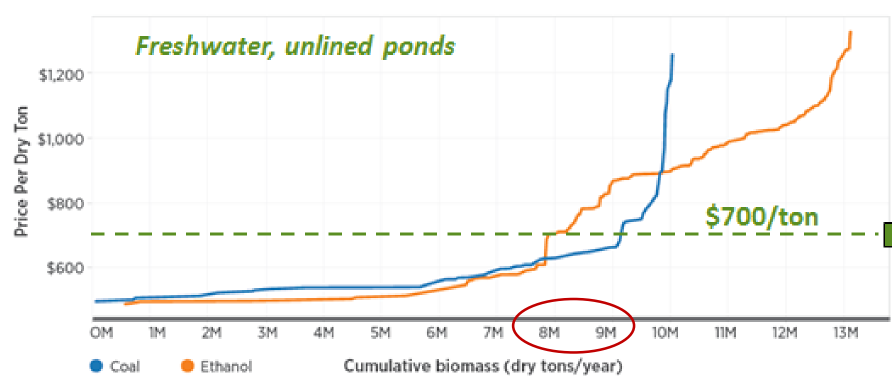
Key Takeaway: CC Enables 10X Higher Biomass Potential





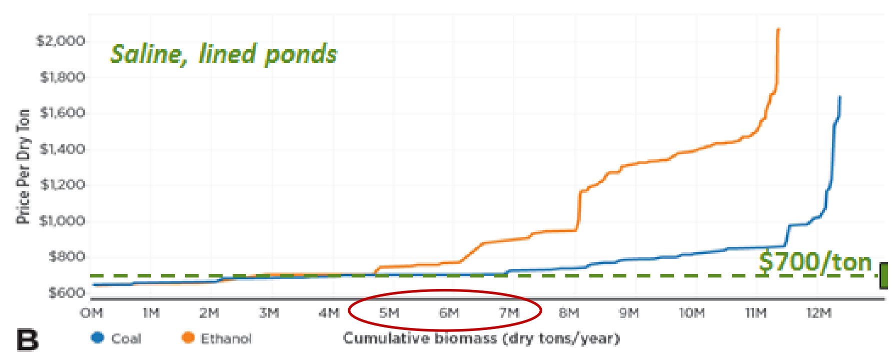
BT16 Study: **12-17 MM tons/yr** biomass possible <$700/ton based on co-located flue gas sourcing

Figure 7.33 | Minimum selling price per dry ton vs. cumulative total biomass for each co-location strategy using *Chlorella sorokiniana* at future productivities[9]



Note: The biomass does not reflect any co-location with natural gas, because the power required to move sufficient CO_2 for the high-productivity scenario brought the cost of CO_2 above the $40/ton commercial purchase price.

Figure 7.35 | Minimum selling price per dry ton vs. cumulative total biomass for each co-location strategy using *Nannochloropsis salina* at future productivities for *(A)* minimally lined ponds and *(B)* fully lines ponds.[11]

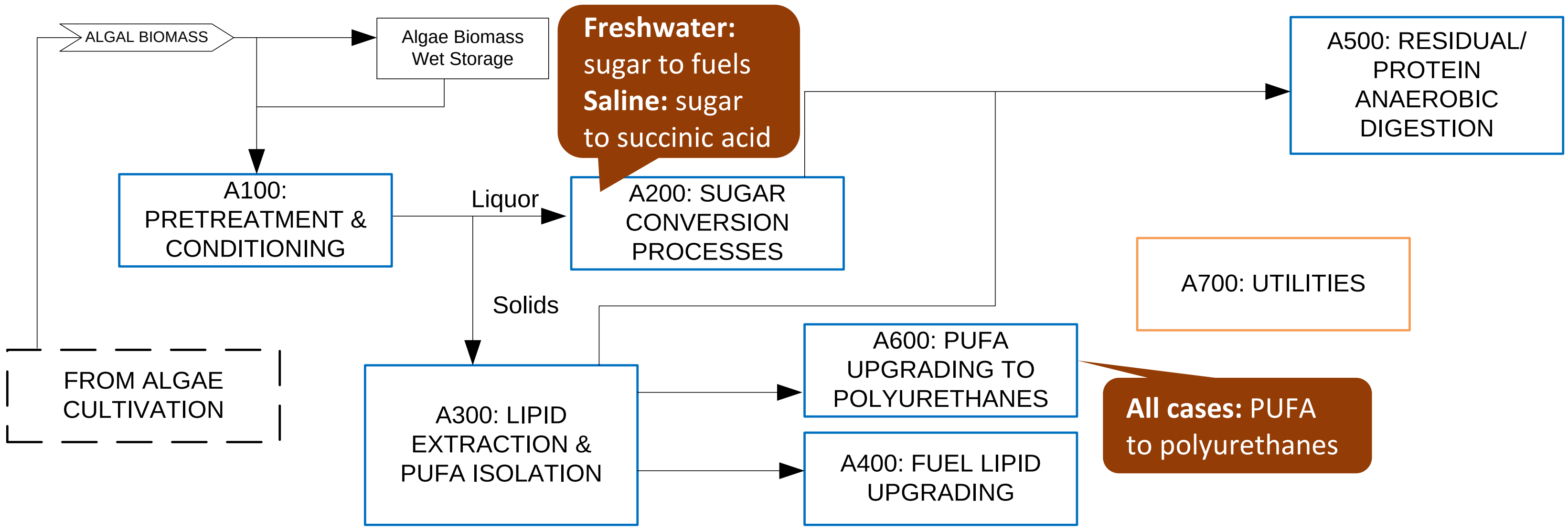


Note: The biomass does not reflect any co-location with natural gas, because the power required to move sufficient CO_2 for the high-productivity scenario brought the cost of CO_2 above the $40/ton commercial purchase price.

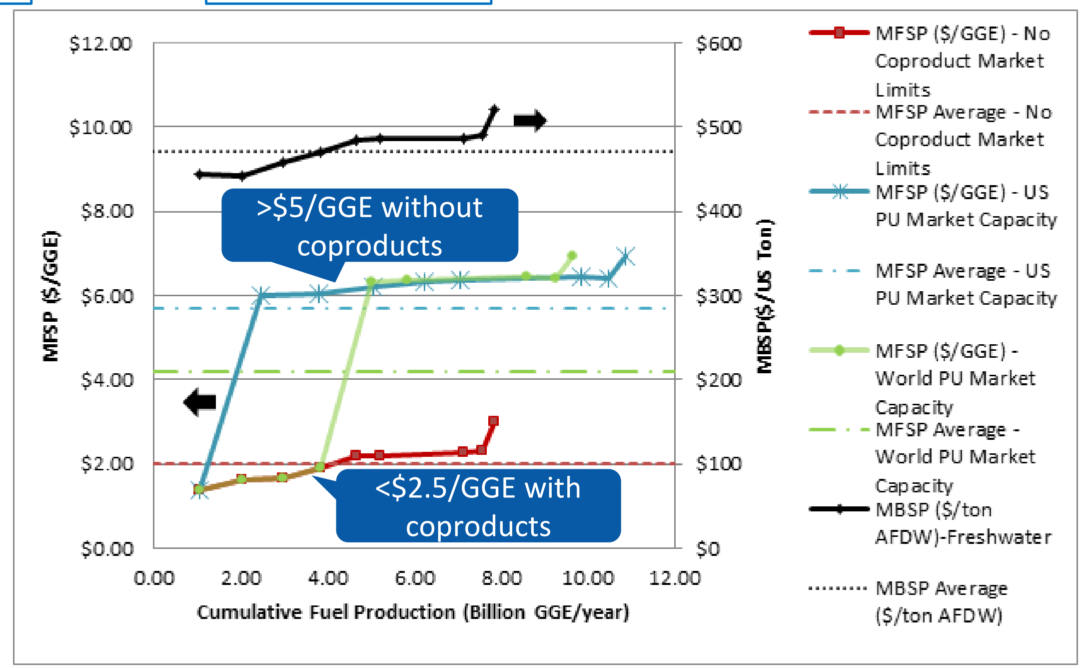
2017 Harmonization: **100-270 MM tons/yr** biomass possible <$700/ton based on CO_2 sourcing via CC

*From Billion Ton '16 Report: https://energy.gov/sites/prod/files/2016/12/f34/2016_billion_ton_report_12.2.16_0.pdf

Harmonization: Conversion to Fuels/Products via CAP

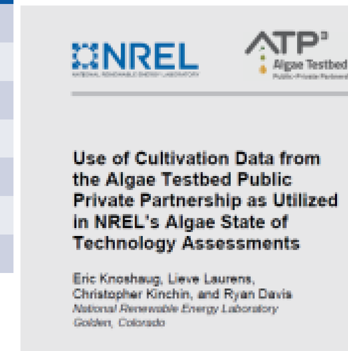


- Evaluated CAP conversion paths to achieve <$2.5/GGE for selected coproduct examples
- Considered over various market limit scenarios (reverted back to fuels after reaching saturation)
- ~1-4 BGGE/yr fuel potential is possible while supporting MFSP goals (in freshwater example) based on market scenarios
- Other coproduct options may further alleviate market limitation concerns – key point highlights ability to achieve MFSP goals with scalable coproducts beyond "niche" markets for a single *proof-of-concept coproduct example*



Technical Accomplishments/Progress/Results: *NREL TEA Sets SOT Benchmarks*

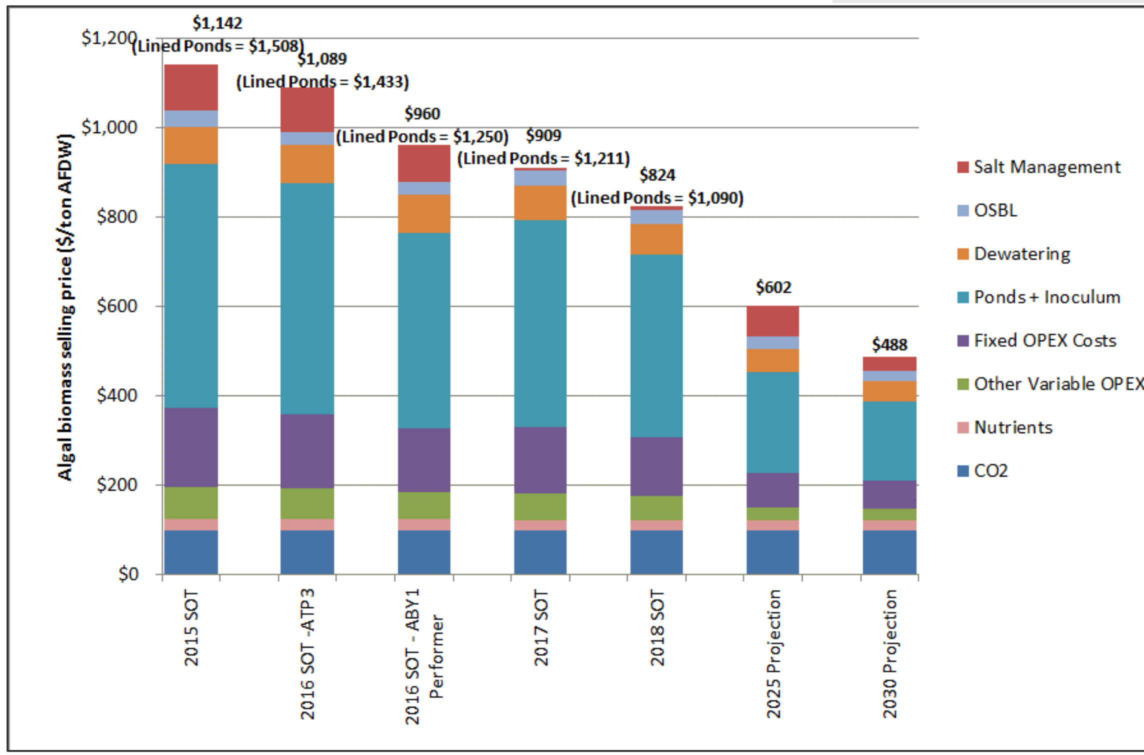
Season	2015 SOT (ATP³)	2016 SOT (ATP³)	2016 SOT (ABY1 Performer)	2017 SOT (ATP³)	2018 SOT (ATP³/ DISCOVR/ RACER)	2025 Projection	2030 Projection
Summer	10.9	13.3	17.5	14.1	15.4	27.7	35.0
Spring	11.4	11.1	13.0	13.2	15.2	24.0	28.5
Fall	6.8	7.0	7.8	8.5	8.5	18.4	24.9
Winter	5.0	5.0	4.8	5.5	7.7	10.0	11.7
Average	**8.5**	**9.1**	**10.7**	**10.3**	**11.7**	**20**	**25**
Max variability	**2.3:1**	**2.7:1**	**3.6:1**	**2.6:1**	**2.0:1**	**2.8:1**	**3.0:1**
MBSP ($/ton, 2016$)	**$1,142**	**$1,089**	**$960**	**$909**	**$824**	**$602**	**$488**



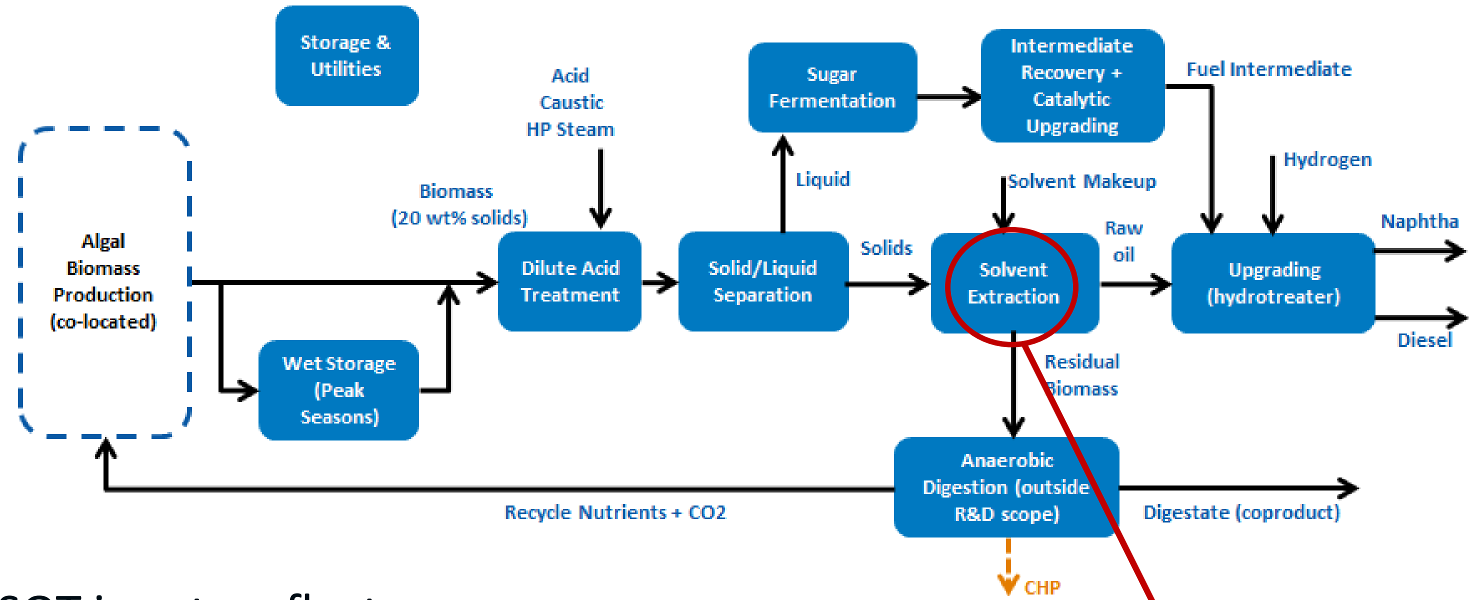
ATP3 cultivation data and methods available at: http://www.nrel.gov/docs/fy17osti/67289.pdf

- Biomass SOT tracked since 2015
- Cultivation data furnished by test-bed partners led by ASU (supplemented by ABY1 industry performer in 2016)
- 2018 supported under ATP3, DISCOVR, RACER – all based on AzCATI test-bed trials
- Yearly improvements:
  - 2016: 7%
  - 2017: 13%
  - 2018: 14%
  - 2030: **5%/year required from 2018 onward**

Strain rotations, operational adjustments

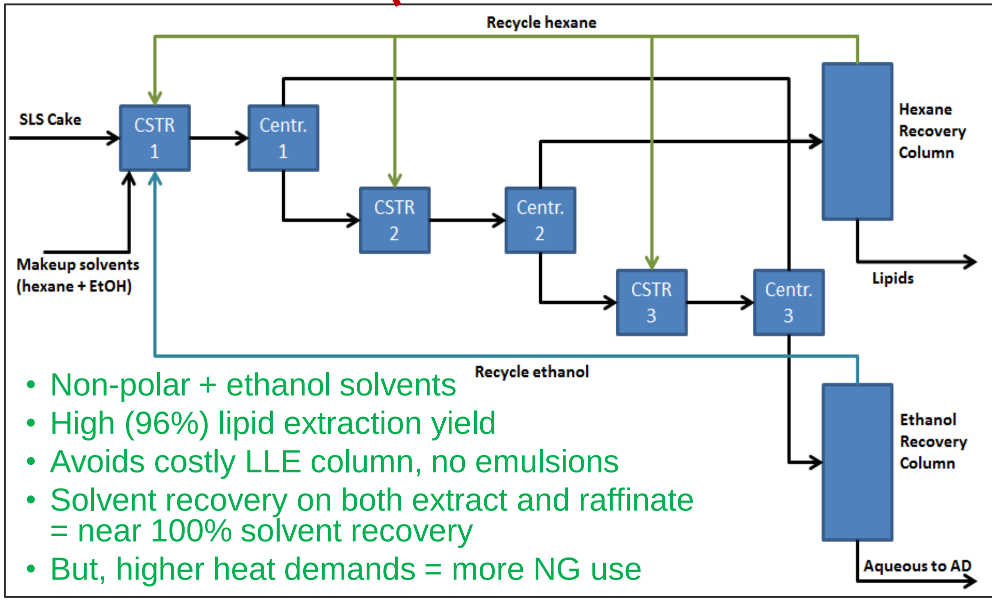


FY18 SOT: CAP Conversion



FY18 SOT inputs reflect:

- Wet seasonal storage of biomass (inputs from INL)
- New 2-solvent extraction with light naphtha product + ethanol (from CPR) → **96% extraction yield**
- Sugars-to-HC fuels via acid fermentation (from CPR)
- Sugars-to-HC fuels via BDO fermentation (from RACER)



CAP Conversion SOT: Benchmark Results, Future Priorities

Processing Area Cost Contributions & Key Technical Parameters	Metric	2018 SOT (CA-AD)	2018 SOT (BDO-AD)	2025 Projection (CA-PU-AD)	2025 Projection (BDO-PU-AD)	2030 Projection (CA-PU-AD)	2030 Projection (BDO-PU-AD)
Fuel Selling Price	**$/GGE fuel**	**$11.15**	**$11.63**	**$3.86**	**$4.08**	**$2.33**	**$2.49**
Net Conversion Contribution	$/GGE	$2.44	$2.79	($3.42)	($3.00)	($3.59)	($3.25)
Feedstock							
Total Cost Contribution	$/GGE fuel	$8.72	$8.84	$7.27	$7.09	$5.92	$5.74
Feedstock Cost (AFDW algae basis)	$/U.S. ton algae	$824	$824	$602	$602	$488	$488
Net Biomass Production Yield	Ton AFDW/Acre-year	17.0	17.0	29.9	29.9	37.2	37.2
Lipid Recovery & Processing							
Total Cost Contribution	$/GGE fuel	$0.32	$0.56	($5.25)	($5.14)	($5.40)	($5.26)
Fractional diversion of lipids to PU coproduct train	% of extracted lipids	NA	NA	46%	46%	46%	46%
PU coproduct yield	g PU/g algae AFDW	NA	NA	0.22	0.22	0.22	0.22

- Two example sugar pathways to fuels (acids, BDO)
- FY18 SOTs focus on maximizing fuel yields (MFSP benefit at high fuel costs >$10/GGE)
- BUT, **fuels alone will not achieve <$3/GGE at ~$500/ton** biomass cost targets
- **Key drivers for future MFSP improvement = biomass cost (productivity), optimize high-value coproducts**
- Some room to further improve core CAP steps (sugar yields, fermentation performance)

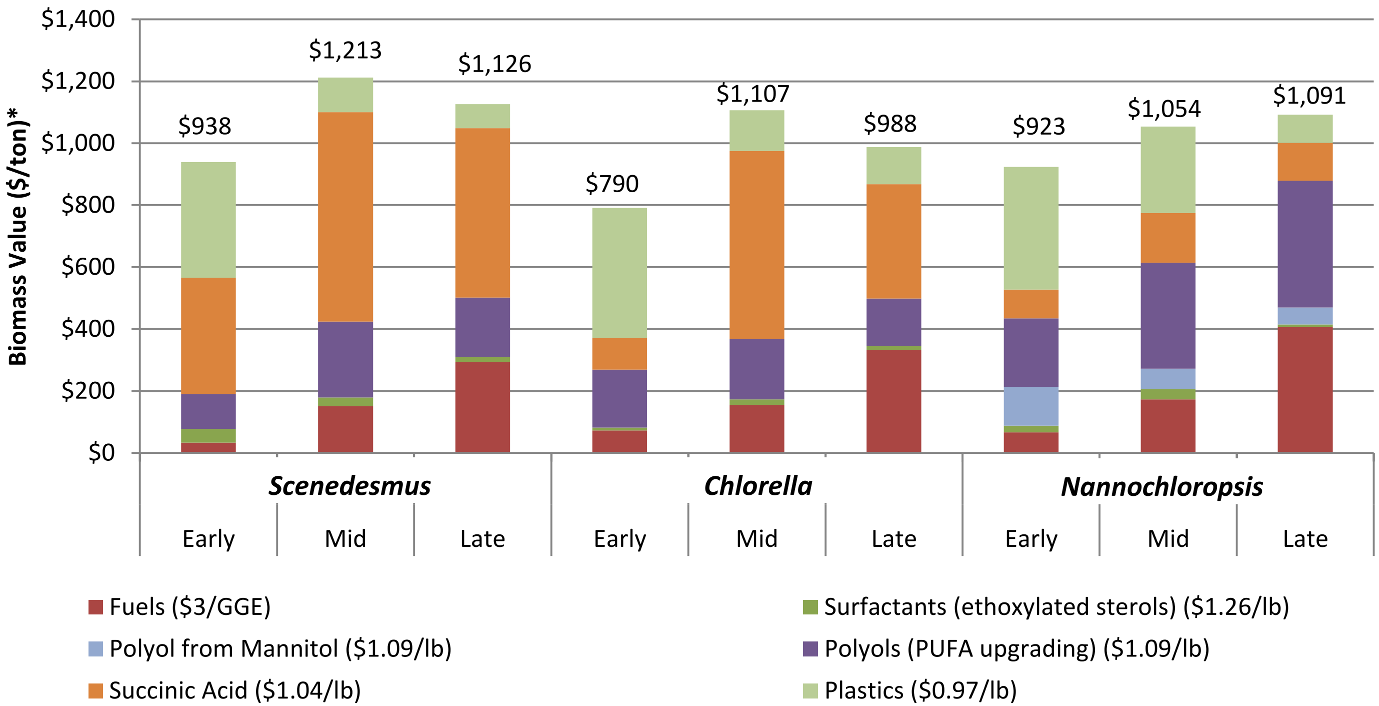
CA – Carboxylic Acids

BDO – 2,3-Butanediol

AD – Anaerobic Digestion

PU- Polyurethane

Technical Accomplishments/Progress/Results: *Algal Biomass Valorization Framework*



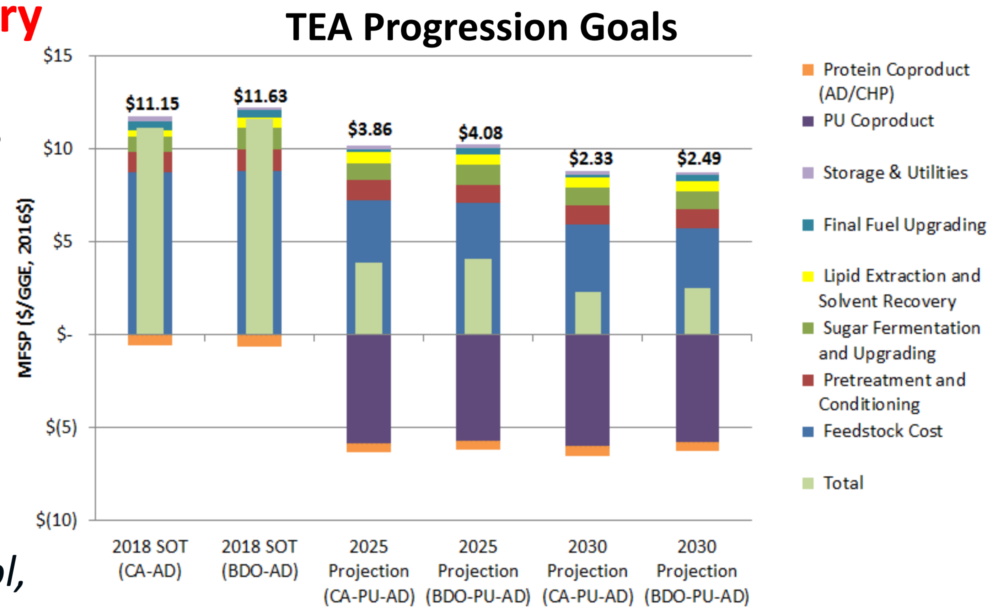
Early/Mid/Late: Stage of nutrient depletion (high-protein to high-lipid)

- Joint effort with ABC project
- Calculates product yields and values vs. time-dependent composition
- *Example results show "how" to exercise model framework to **identify biomass cost vs quality optima** – but not yet inclusive of full processing costs (capex, power, etc. – will reduce values in plot)
- After full TEA, if cumulative "value" exceeds MBSP = profitable

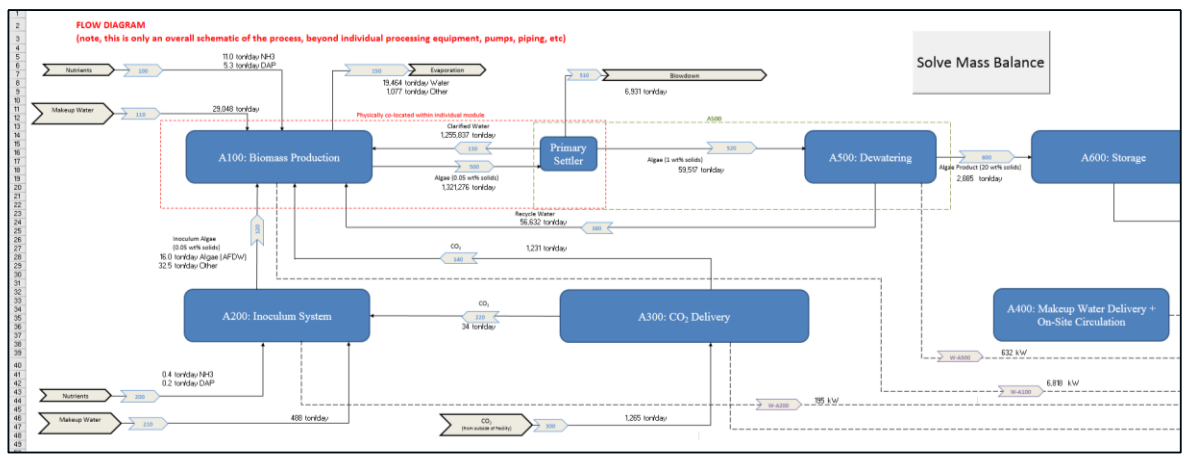
Relevance

TEA modeling is highly relevant to industry and BETO goals:

- **Guides R&D/DOE decisions, sets targets**
  - Technical targets (yields, process performance)
  - Cost targets (basis for BETO MYP goals)
- Identifies key directions (pathways, coproduct opportunities, etc.)
- Facilitate interaction between stakeholders in industry, research, DOE
  - *Example: Outreach to GAI, MicroBio, Algenol, Clearas, Algenesis for TEA discussions*



- **Foster collaboration** with other modeling groups (ANL, PNNL, ORNL, INL), BETO consortia (ATP3, DISCOVR, Sep-Con)



- **Public dissemination** of models: e.g. Excel-based algae farm TEA tool now available publicly: https://www.nrel.gov/extranet/biorefinery/aspen-models/

Future Work

- Algae cultivation on wastewater *(Q1 FY19, complete):*
  - Preliminary TEA to understand cost vs resource potential for algal biomass production via wastewater treatment, valorization of N/P mitigation
  - High value for WWT credits, but also must understand national scalability (BGY fuel potential)
- Biomass growth versus quality modeling *(Q2 FY19, joint with NREL ABC project):*
  - Evaluate trade-offs between productivity vs. composition on resultant "intrinsic value" of biomass for fuels/products
  - Expand on initial "intrinsic value" framework from FY17 to **include full processing TEA; identify optimal biomass cost/composition** point(s) to target for tailored CAP configuration
- FY19 CAP design report update *(FY19: first draft Q3, final draft Q4):*
  - **Establish new design report** documenting CAP pathway strategy for **$2.5/GGE algal biofuels** with applicability for commodity fuel production alongside scalable coproducts
  - Analysis will consider at least one scenario for reasonable biomass *cost + composition* targets
  - First draft (Q3) will be **subjected to external peer review vetting process** before finalizing in Q4
- SOT benchmarking for biomass production + CAP conversion *(Q4 FY19, beyond)*
- TEA support for DISCOVR Consortium *(ongoing):*
  - Provide guidance and feedback to DISCOVR leadership on key areas to improve models, close gaps; incorporate test-bed data to inform future SOT benchmarks

Summary

1) Overview: This project supports BETO by translating R&D into economics using TEA modeling, tracking progress towards future targets
2) Approach: Aspen Plus process modeling coupled with economic analysis. Supports industry via design reports, communication with stakeholders, external collaborations
3) Technical accomplishments: NREL algae TEA project has made important achievements since 2017 peer review
    - Coordinated a new algae harmonization study joint between four modeling groups, highlighted opportunities for algae CCU and coproducts
    - Substantial work in FY18 to demonstrate the need for high-value coproducts in supporting <\$2.5/GGE MFSP goals at commodity scales
    - Established new SOT benchmarks for biomass production and CAP conversion through two sugar-to-hydrocarbon pathways
    - Initiated biomass valorization framework concept, to be expanded upon in FY19 to identify optimal growth/composition points
4) Relevance: TEA work is highly relevant to supporting program directions for BETO, near- and long-term R&D priorities for NREL/partners based on cost drivers
5) Future work: Expand on growth vs composition modeling, establish new design case
    - Further efforts moving forward may focus on novel opportunities to upgrade/valorize protein (led by NREL R&D activities) to relax constraints on CAP configurations currently focused on carbs/lipids

NREL, Sept, 2010, Pic #18229

Acronyms

- AD = anaerobic digestion
- AFDW = ash free dry weight
- BDO = 2,3-butanediol
- CA = carboxylic acids
- CAP = Combined Algae Processing (biochemical algae conversion process)
- CC = carbon capture
- Design case = future technical target projections to achieve TEA cost goals
- GGE = gallon gasoline equivalent
- MBSP = minimum biomass selling price
- MFSP = minimum fuel selling price
- MYP = BETO's Multi-Year Plan (formerly MYPP = Multi-Year Program Plan)
- PU = polyurethanes
- SOT = state-of-technology (annual benchmarking to update TEA based on latest R&D data)
- TEA = techno-economic analysis

Thank You

www.nrel.gov
www.nrel.gov/bioenergy/algal-biofuels.html

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Additional Slides

Response to Reviewers' Comments (2017 Review)

- The continued development of sound and relevant TEA for the use of defining and identify gaps within the current knowledge base of large scale algal biofuel production is important. These studies have a great research impact as they provide a blueprint for current or needed optimization within the field. More interaction with large scale production cultivators may help to focus the TEA.
- We agree that knowledge gaps remain in projecting these technologies out to n^{th}-plant commercial scale, and further opportunities exist to continue refining and improving the models. We plan to continue focusing on this moving forward, for example through planned subcontracts to improve modeling fidelity/capabilities around tracking CO_2 uptake and assimilation into ponds over a range of dynamic conditions, as well as to provide engineering support in establishing TEA models for new coproduct processing trains. Additionally, we do have a number of working relationships with stakeholders in industry, and hope to continue those discussions and to reach out to others to leverage existing knowledge they've established in validating or improving our models. We always welcome such inputs, and also would gladly seek similar guidance from other related industries (e.g. nutraceutical producers).

- This project is one of the essential core elements of the portfolio. Its past and future work provide unbiased data for BETO and industry to direct their resources. Continued emphasis on co-products is critical.
- We thank the reviewers for their positive feedback in recognizing the utility of this project for BETO and the algae community. We also agree further emphasis on co-products will be key in highlighting paths towards achieving economic viability for an algal biorefinery based (in part) on producing commodity fuels. The majority of work conducted in FY18 placed particular emphasis on evaluating both the TEA potential for various co-product opportunities, as well as product volume scalability in the marketplace and how much fuel could be supported on a national level for selected example co-products. Moving forward, we hope to expand the TEA models to include additional coproduct options, recognizing that doing so requires detailed process modeling for complex operations.

Publications and Presentations

Publications (since 2017 review):

- ANL, NREL, PNNL (R. Davis, coordinating author). "2017 Algae harmonization report: Evaluating the potential for future algal biofuel costs, sustainability, and resource assessment from harmonized modeling." Joint technical report ANL-18/12; NREL/TP-5100-70715; PNNL-27547, August 2018. https://www.nrel.gov/docs/fy18osti/70715.pdf
- S. Leow, B.D. Shoener, Y. Li, J.L. DeBellis, J. Markham, R. Davis, L.M.L. Laurens, P.T. Pienkos, S.M. Cook, T.J. Strathmann, J.S. Guest. "A unified modeling framework to advance biofuel production from microalgae." *Environmental Science & Technology*, October 2018; DOI: 10.1021/acs.est.8b03663.
- L.M.L. Laurens, J. Markham, D.W. Templeton, E.D. Christensen, S. Van Wychen, E.W. Vadelius, M. Chen-Glasser, T. Dong, R. Davis, P.T. Pienkos. "Development of algae biorefinery concepts for biofuels and bioproducts; a perspective on process-compatible products and their impact on cost-reduction." *Energy & Environmental Science*, 2017, 10, 1716-1738.
- H. Cai, J. Dunn, A. Pegallapati, Q. Li, C. Canter, E. Tan, M. Biddy, R. Davis, J. Markham, M. Talmadge, D. Hartley, D. N. Thompson, P. A. Meyer, Y. Zhu, L. Snowden-Swan, S. Jones. "Supply Chain Sustainability Analysis of Renewable Hydrocarbon Fuels via Indirect Liquefaction, Fast Pyrolysis, and Hydrothermal Liquefaction: Update of the 2016 State-of-Technology Cases and Design Cases." ANL technical report, March 2017. https://greet.es.anl.gov/publication-renewable_hc_2016_update

Presentations (since 2017 review):

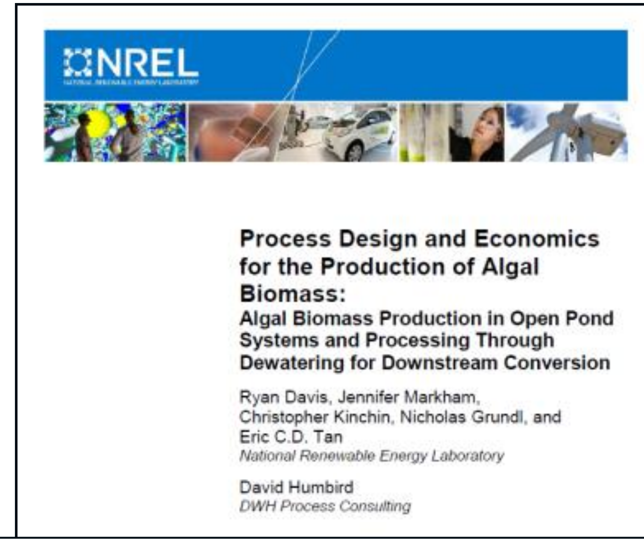
- R. Davis, J. Clippinger, "2017 Algae harmonization study: projections for future algal biorefineries from harmonized modeling." Presented at the 2018 Algae Biomass Summit, The Woodlands, TX, October 2018.
- J. Markham, "Techno-economic analysis for the production of algal biomass in closed photobioreactors: process, design, and cost considerations for future commercial algae farms." Presented at the 2017 Algae Biomass Summit, Salt Lake City, UT, October 2017.

Backup Slides

Harmonization Approach: CO2 Sourcing

- Algae = high CO_2 demands (~2 lb/lb)
- Historical algae studies typically assume CO_2 via bulk flue gas (e.g. *Billion Ton '16,* prior harmonization efforts)
- But, numerous logistical/practical challenges for bulk flue gas:
  - Off-site: Constrained to <10 miles to remain economical (power vs capex) = limited national scalability
  - Off-site: NREL algae farm report: 15 km pipeline = ~75 MW compressor, cannot "shut off" every night – for 24-hr operation, *higher power demand to run compressor than the amount of power generated to produce the CO_2*
  - On-site: Expensive and logistically challenging to route 4-5 ft FG pipelines around a farm >1,000 acres
  - Flue gas may constrain biomass product options
  - CO_2 concentration varies by source; energetics used to move non-CO_2 gas

→ **Solution: flue gas carbon capture**


NREL

Process Design and Economics for the Production of Algal Biomass:
Algal Biomass Production in Open Pond Systems and Processing Through Dewatering for Downstream Conversion

Ryan Davis, Jennifer Markham, Christopher Kinchin, Nicholas Grundl, and Eric C.D. Tan
National Renewable Energy Laboratory

David Humbird
DWH Process Consulting

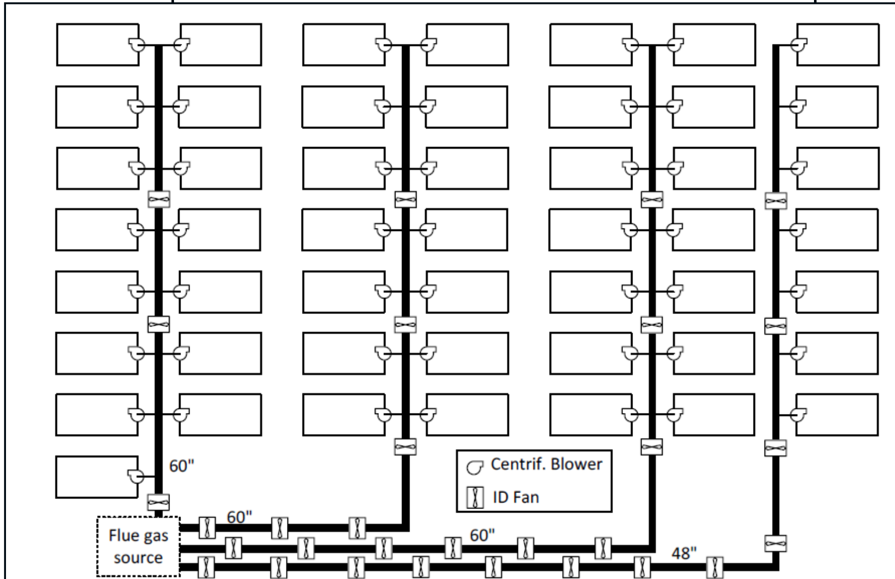


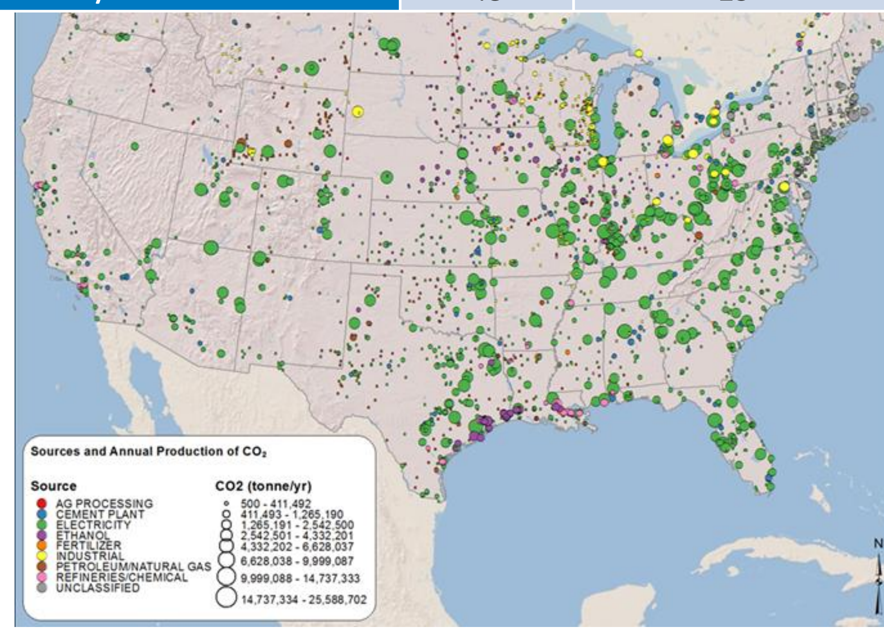
Figure 17. Layout of flue gas piping and fans for the 50-module system

NREL algae farm report: https://www.nrel.gov/docs/fy16osti/64772.pdf

Harmonization: Carbon Capture

- CC: less costly and logistically challenging (8X lower on-site delivery costs)
- Relaxes constraints for flat, unoccupied land co-located with power plant
- BAT: New CO_2 Supply, Demand and Transport Model via CC sourcing
  - Supply: Comprehensive, national-scale, non-competitive waste CO_2 sources; assume 80% capture rate
  - Demand: Dynamic operations using pond temperature and biomass growth models
    - Strain rotation (3 fresh; 2 saline)
    - Pond depths (15, 20, 25 cm)
    - Maximize site-specific productivity
    - 330-days of operation
    - 20 g/m^2/day (mean annual) minimum economic threshold; sites < 20 removed
    - Establish total site-level CO_2 requirement

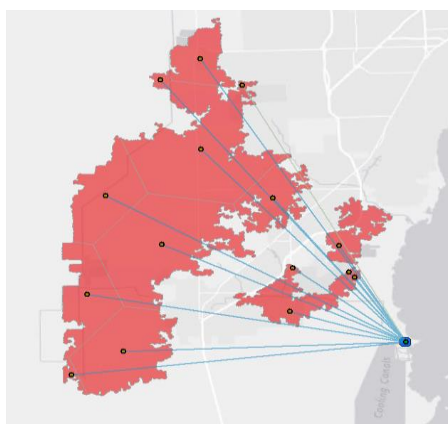
CO_2 Source	# of Facilities	U.S. Emissions (million metric tons/yr)
Coal-Fired Power Plant	1,339	2,677
Metal Production	294	525
Natural Gas-Fired Power Plant	1,774	394
Chemical Plants and Hydrogen Production (including refineries)	611	315
Ethanol Production Plant	317	140
Petroleum and Natural Gas Processing	1,489	113
Cement Plants	181	83
Pulp and Paper Mills	227	38
Fertilizer/Ammonia Plants	48	25

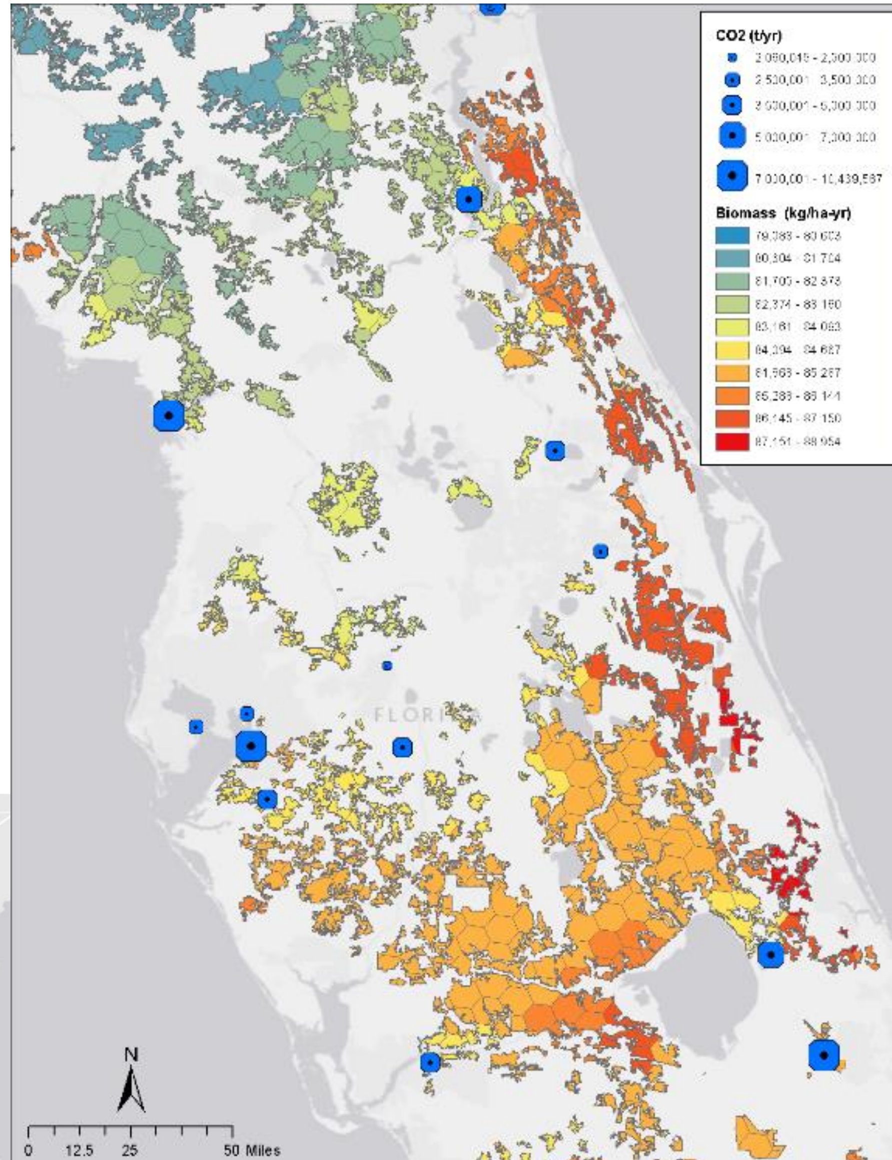


Slide Credit, Andre Coleman (PNNL)

BAT CO2 Modeling Logistics for Sourcing via Carbon Capture

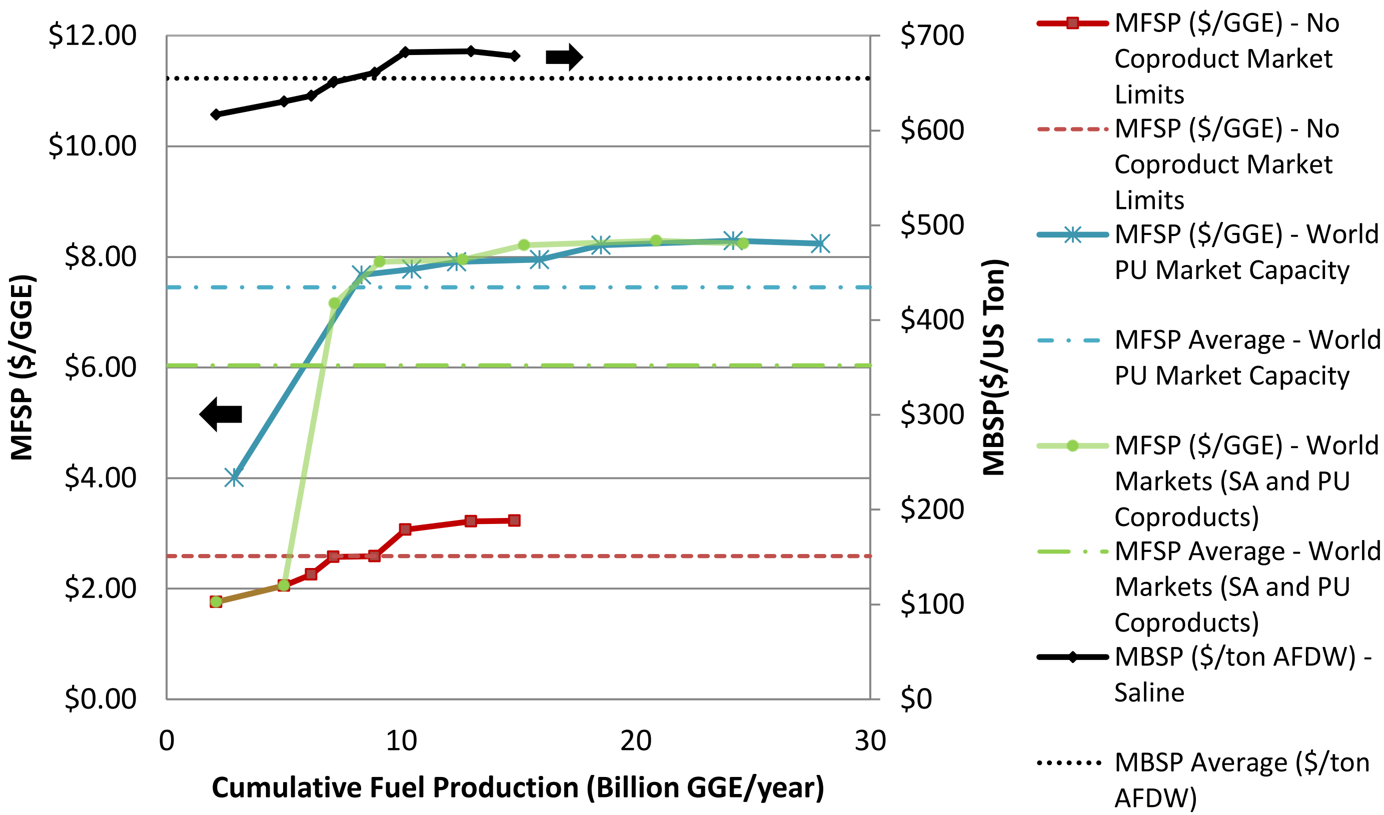
- Capture and Transport
  - Location-allocation spatial network model developed to optimize pipeline route and associated transport costs
  - CO_2 source can supply many sites; sites can receive multiple CO_2 sources
  - Costs established for capture (based on source), compression, and pipeline right-of-way, material, diameter, distance, pumps (based on CO_2 mass) for each source
  - Costs established for pipeline construction, labor, and maintenance (assumed 30-yr life)
  - Sites w/ delivery costs ≥ $55/tonne removed
  - Unique cost solution for each source/target





Slide Credit, Andre Coleman (PNNL)

Harmonization: CAP Pathway Results: MFSP vs Fuel Potential (Saline Example)



- Three scenarios considered for coproduct volume limits:
  - World polyurethane market
  - World polyurethane + succinic acid (and derivatives) markets
  - No market limit (example case for maximum coproduct allowances)
- Saline considered world market volumes due to granularity of site groupings and larger biomass outputs per site group
- Again, NOT intended to assert that algae would subsume entire product market shares; only reflected this way to show tradeoffs between fuel potential vs fuel cost for a *proof-of-concept example* coproduct (many other products possible for diversified biorefineries)

Harmonization: CAP Pathway: Cumulative TEA Results

Site group	Weighting (# of 5,000-acre farms in group)	Fuel yield from algae (GGE/ton)	Cumulative BGGE/yr fuel output (from algae alone)	Cumulative MM ton/yr coproduct output	Cumulative weighted average MFSP ($/GGE)
Freshwater scenario					
8	66.0	76.1	1.1	3.55 PU	$1.39
5	63.3	75.5	2.0	6.76 PU	$1.50
4	59.4	75.8	3.0	9.86 PU	$1.55
7	58.7	75.3	3.9	12.71 PU (s)[1]	$1.64
9	56.8	108.8	5.0	12.71 PU (s)	$2.51
1	40.1	108.7	5.9	12.71 PU (s)	$2.96
3	134.0	108.3	8.6	12.71 PU (s)	$3.93
6	31.4	108.6	9.3	12.71 PU (s)	$4.09
2	22.1	106.4	9.7	12.71 PU (s)	$4.20
Saline scenario					
7	199.2	54.4	2.1	5.28 PU + 5.56 SA	$1.76
4	264.6	54.2	5.0	12.02 PU + 12.67 SA	$1.93
8	106.0	109.7	7.2	12.90 PU + 12.67 SA (s)[1]	$2.90
6	96.8	108.5	9.1	12.90 PU + 12.67 SA (s)	$3.63
3	171.8	108.9	12.6	12.90 PU + 12.67 SA (s)	$4.51
1	119.5	108.4	15.3	12.90 PU + 12.67 SA (s)	$4.98
2	261.9	108.0	20.9	12.90 PU + 12.67 SA (s)	$5.69
5	194.3	107.9	24.6	12.90 PU + 12.67 SA (s)	$6.04

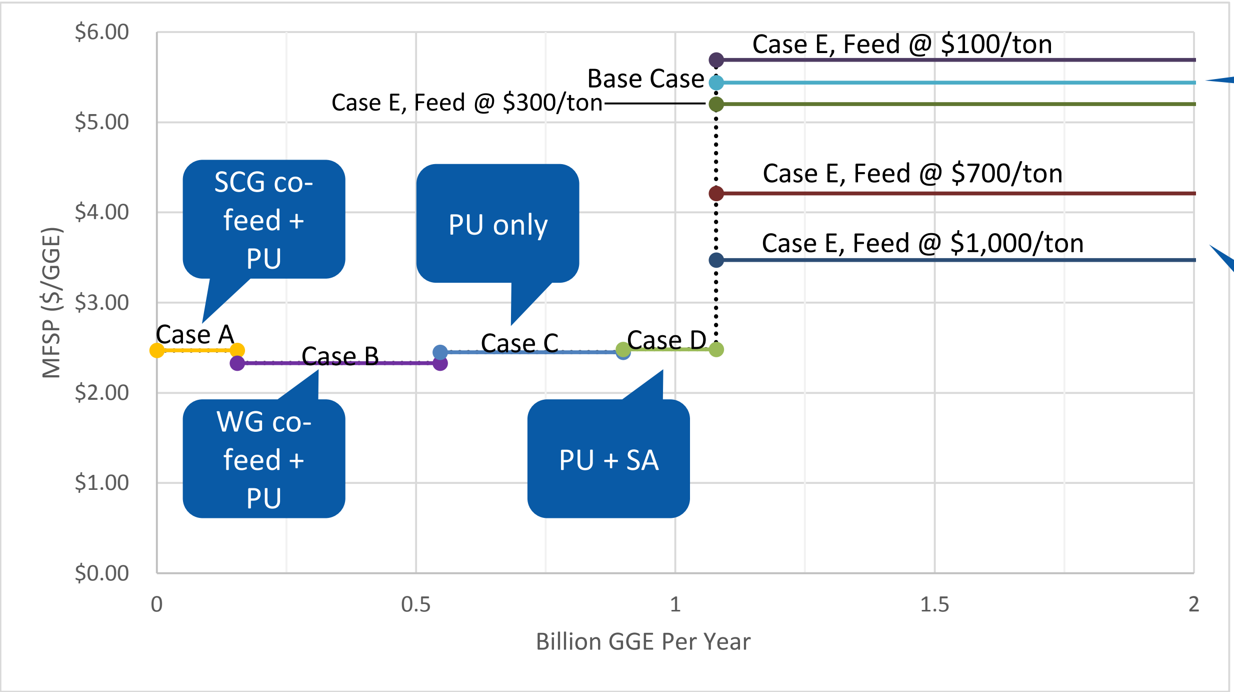
- When taken cumulatively, "green curves" support up to 5 BGGE/yr fuel potential at <$2.50/GGE
- Enabled by PU coproduct alone for freshwater, PU + SA for saline
- "World volumes" for those two products may equate to <100% US volumes when diversified to other product options (beyond the scope of this work)

[1] (s) = saturation limit. Values for CAP pathway shown above are for green curves of MFSP plots, based on coproduct outputs modeled up until reaching world market saturation limits (for example purposes).

Technical Accomplishments/Progress/Results: *Demonstrating Scalability for MFSP Targets*

- Beyond only demonstrating “a path” to achieve <$2.5/GGE, must also ensure that path is scalable to national commodity scale to support “meaningful” biofuel capacity
- Go/No-Go: Demonstrate a path (example) to achieving <$2.5/GGE goals while simultaneously ensuring national scale fuel potential remains ≥1 BGGE/yr
- Maintained similar example coproducts as other recent work (PU, SA), plus two waste co-feeding options appropriate for CAP (spent coffee grounds, waste grease)
- Also considered protein via animal feed scenarios

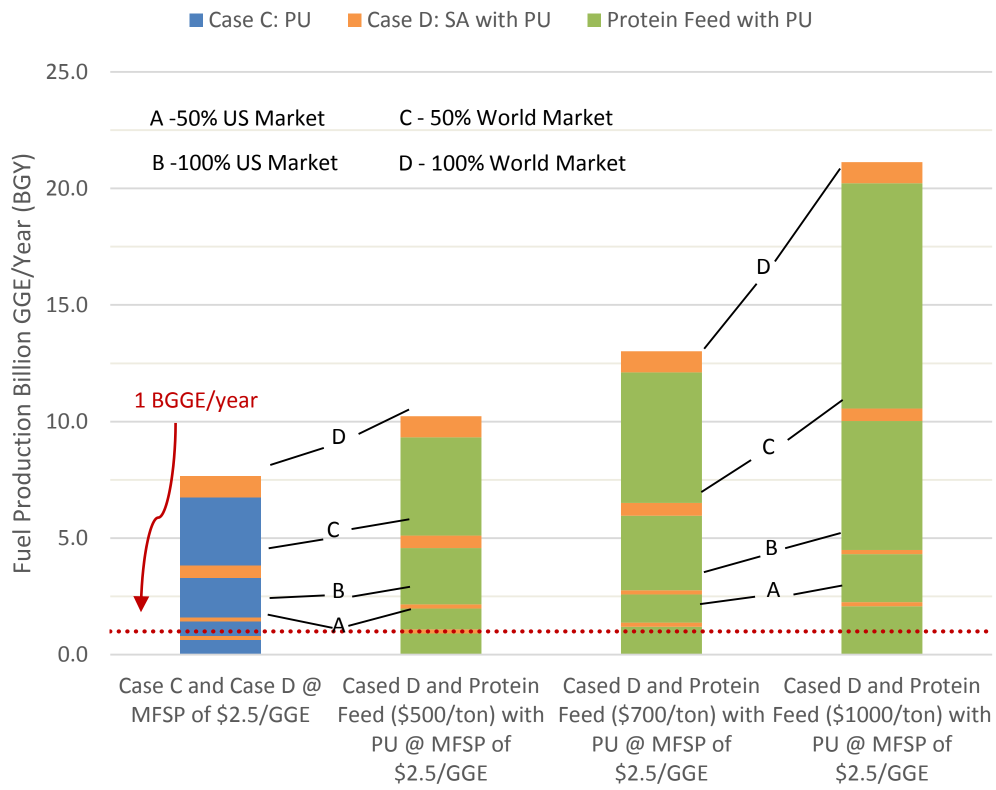
All cases limited to 50% of US market volumes



Base case = AD

If protein comes last after exhausting other options, cannot meet $2.5/GGE by itself

Scalability Improves When Simultaneously Including Protein Valorization



- When also valorizing protein at $500/ton or more (whether animal feed or otherwise), can get to considerably higher fuel potential as lipid diversion to PU can be relaxed
- All findings based on HCSD biomass composition basis; future work to consider alternative/higher-protein biomass scenarios for different CAP configurations

Algae Farm Model: Tracking Biomass SOT Benchmarks

	Productivity, g/m²/day	Harvest Density, g/L	Evaporation Rate, cm/day	Algae Strain	Harvests per week	Harvest volume, fraction of pond	Daily dilution rate, fraction of pond
2015 SOT (Florida Algae)							
Fall 2014	6.8	0.22	0.01	Nanno	1x	0.75	0.11
Winter 2014	5.0	0.23	0.01	Nanno	1x	0.75	0.11
Spring 2014	11.4	0.36	0.14	Nanno	1x	0.75	0.11
Summer 2014	10.9	0.25	0.02	Nanno	1x	0.75	0.11
Average	**8.5**	**0.27**	**0.04**				
2016 SOT (Florida Algae)							
Fall 2015	7.0	0.20	0.01	Desmo	3x	0.50	0.21
Winter 2014[a]	5.0	0.23	0.01	Nanno	1x	0.75	0.11
Spring 2015	11.1	0.28	0.14	Nanno	3x	0.25	0.11
Summer 2015	13.3	0.32	0.02	Desmo	3x	0.50	0.21
Average	**9.1**	**0.26**	**0.04**				
2016 SOT (ABY1 Performer)							
Fall	7.8	0.20	0.01	Nanno	Not provided		
Winter	4.8	0.23	0.01	Nanno	Not provided		
Spring	13.0	0.28	0.14	Nanno	Not provided		
Summer	17.5	0.32	0.02	Nanno	Not provided		
Average	**10.8**	**0.26[b]**	**0.04[b]**				
2017 SOT (ASU)							
Fall 2016	8.5	0.30	0.7	Nanno	NA (batch mode, harvested every 1-3 weeks)		
Winter 2016	5.5	0.36	0.2	Kirch	NA (batch mode, harvested every 2-3 weeks)		
Spring 2016	13.2 (ARID)	0.74	0.9	Scened	5x	0.25	0.18
Summer 2015[c]	14.1	0.32	1.2	Desmo	3x	0.50	0.21
Average	**10.3**	**0.43**	**0.7**				
2018 SOT (ASU)							
Fall 2016[d]	8.5	0.30	0.7	Nanno	NA (batch mode, harvested every 1-3 weeks)		
Winter 2018	7.7	0.69	0.2	Scened/Monor	NA (batch mode, harvested every 10-13 days)		
Spring 2018	15.2	0.70	0.9	Monor	1-3x	0.83	0.17
Summer 2018	15.4	0.35	1.2	Desmo X2	3x	0.55	0.20
Average	**11.7**	**0.51**	**0.7**				

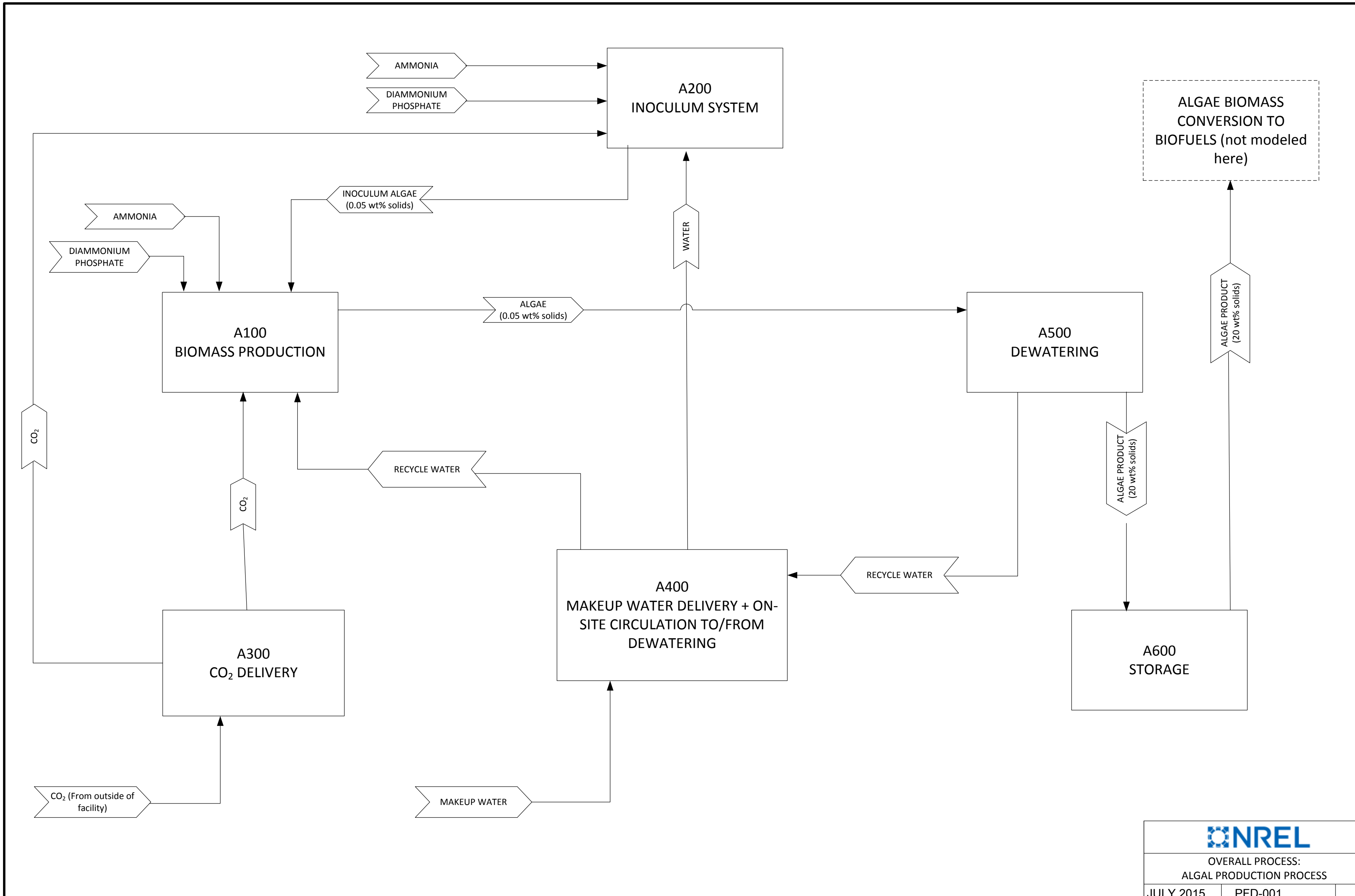
[a] No new winter 2015 data available; winter 2014 data at Florida Algae is maintained for 2016 SOT.
[b] Harvest densities and evaporation rates were not provided; set consistent with the 2016 ATP³ SOT basis.
[c] No new summer 2016 data available; summer 2015 data at ASU is maintained for 2017 SOT.
[d] No new fall 2017 data available; fall 2016 data at ASU is maintained for 2018 SOT

- 2015 SOT: Focus was on establishing a baseline using most consistent strains/protocols possible
- 2016 SOT: Same site (FA) given best performance and relevance to BETO harmonization priorities, but allowed for alternative strains/protocols
- 2017 SOT: Logistical constraints for ATP3 forced moving the SOT basis to ASU site (FA no longer available), strains as available for cultivation data (different each season), and different pond designs/harvest strategies (only basis available)
- 2018 SOT: Moved more towards hypothesis-driven research, intentional strain rotation seasonally, different pond operation approaches (shallow depth in cold seasons etc)
- Based on ATP3, DISCOVR, RACER activities

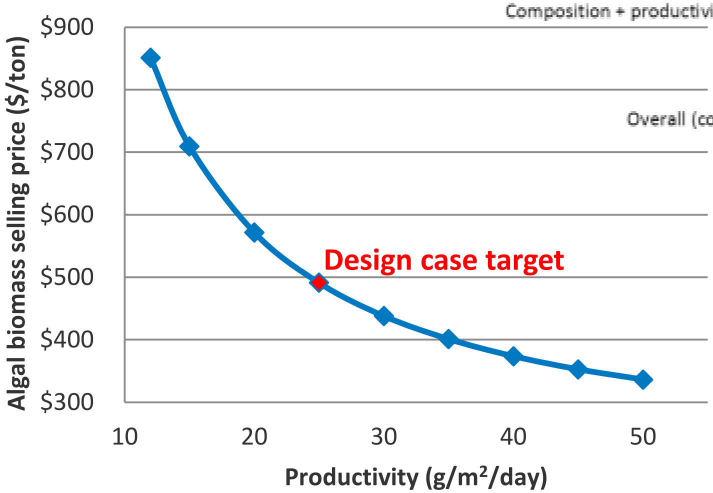
FY18 SOT: CAP Experimental Metrics

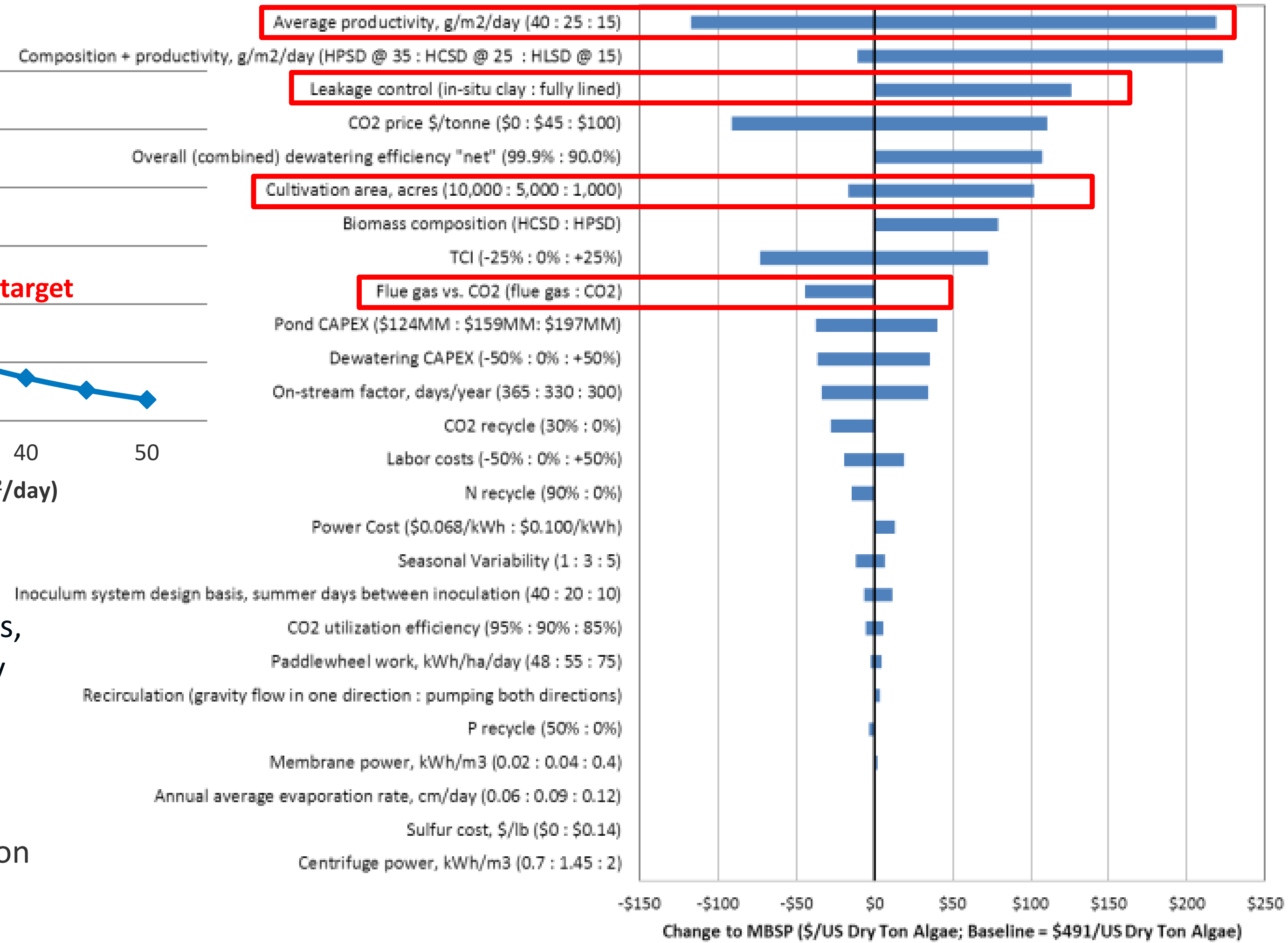
Pretreatment	**Value**		**Experimental Notes**
Solids loading (wt%)	20% [1]		-PT data originally based on HLSD experiments averaged across 8 runs, extrapolated same conversions to HCSD -SLS vacuum membrane based on new FY17 data
Acid loading (wt% vs feed liquor)	2%		
Fermentable sugar release	74%		
Carbs to degradation products	1.5%		
Hydrolysate solid-liquid separation	Yes (vacuum belt filter with flocculent)		
Sugar loss	5%		
Lipid loss	0.5%		
SLS flocculent loading (g/kg IS)	10		
SLS membrane capacity (kg IS/m^2-h)	30		
Sugar Fermentation	**Acids**	**BDO**	
Fermentation productivity (g/L-hr)	0.3	56 hour batch	Acids data based on ABC/CPR Q2 milestone; BDO data based on inputs from NREL researchers under recent RACER fermentation work on *Desmodesmus* C046
Sugar diversion to organism seed growth	*10%* [2]	*10%* [2]	
Glucose utilization to product	92% [3]	74% [3]	
Mannose utilization to product	92% [3]	55% [3]	
Glycerol utilization to product	92%[3]	0%[3]	
Butyric acid yield (g/g total available sugars)	0.41	NA	
Acetic acid yield (g/g total available sugars)	0.10	NA	
BDO yield (g/g total available sugars)	NA	0.34	
Acetoin yield (g/g total available sugars)	NA	0.10	
Catalytic upgrading: overall yield to HDO feed (wt% vs recovered fermentation intermediate) [4]	53%	60%	
Lipid Extraction + Upgrading			
Extraction configuration	3-stage CSTR + centrifugation with 2 solvents		-Extraction yields based on HCSD biomass, new FY18 data with light naphtha solvent -Hydrotreating (HDO+HI) yields based on HCSD-extracted lipids, maintaining FY17 data for one-step HDO + HI upgrading
Solvent loading (nonpolar: EtOH: dry biomass, wt)	2.7:1.1:1 g/g/g		
CSTR extraction residence time (min)	15		
Convertible lipid extraction yield per step	74% - 65.4% - 55.6%		
Total convertible lipid extraction yield	95.7%		
Non-sterol lipid impurity partition to extract	<11.5%		
Hydrotreating conditions	707 °F, 435 psig, ~5,900 scf/bbl H_2 feed ratio		
Catalyst details	1% Pt/SAPO-11, WHSV = 1 hr^{-1}		
Hydrotreating RDB yield (wt% of oil feed) [5]	63.4%		
Hydrotreating Naphtha yield (wt% of oil feed) [5]	21.0% [6]		
Hydrotreating H_2 Consumption (wt% of oil feed)	2.55% [7]		

Algae Farm Design Report: Process Schematic



Algae Farm Model: Sensitivity Analysis– Productivity Drives TEA

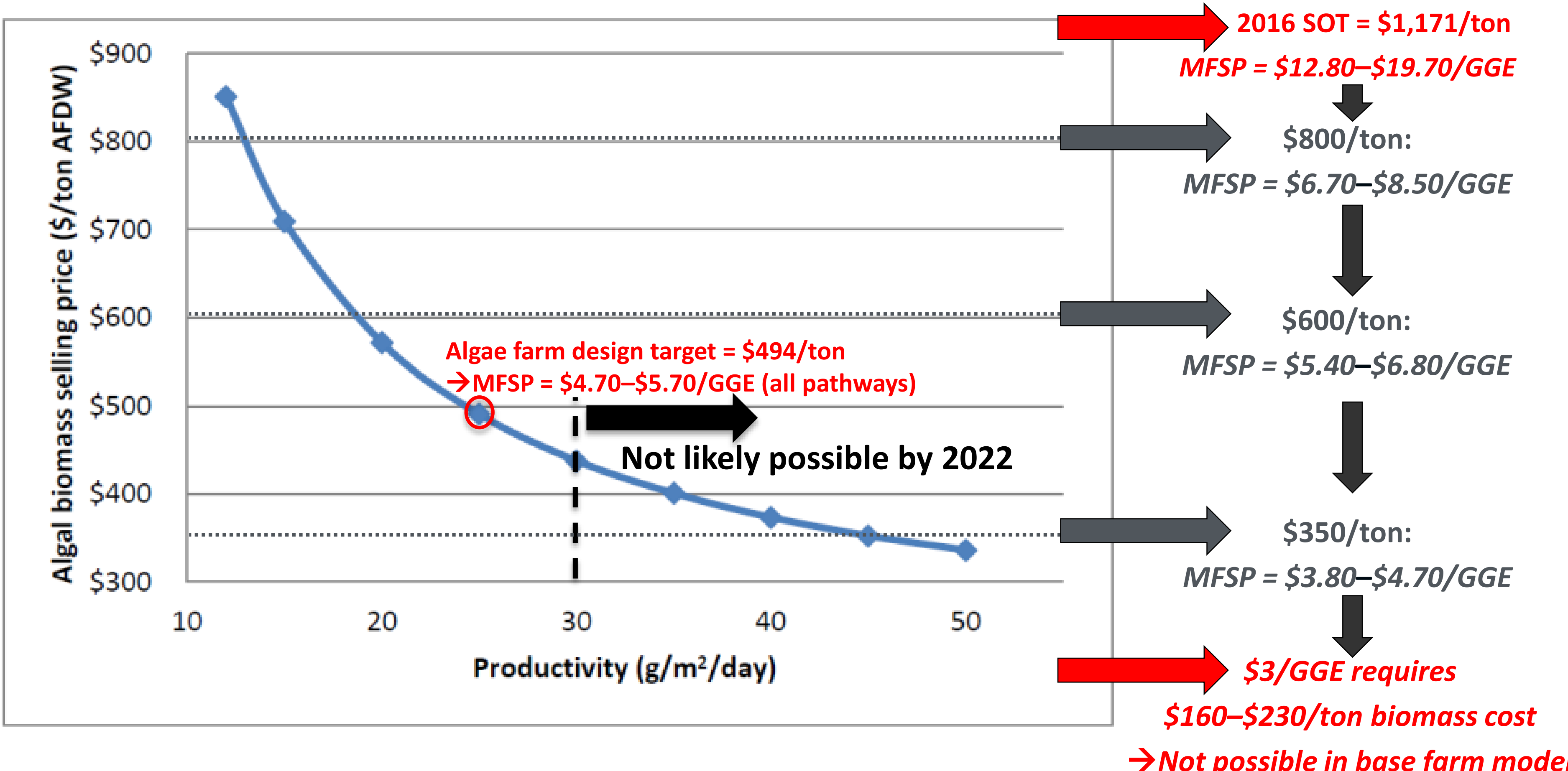




Key drivers:

- Productivity: dictates economics, critical to achieve ≥25 g/m²/day
- Liners: adding full pond liners = ≥$120/ton MBSP penalty ($0.85/GGE impact on MFSP)
- Farm size: 1,000 acres = $100/ton MBSP penalty ($70 labor + $30 capex)
- CO2 cost/sourcing
  - Price for purchased CO_2 (flue gas CCS) $0–$100/tonne = ±$100/ton MBSP
  - Additional scenarios considered for flue gas: 15-km flue gas transport infeasible
  - Flue gas co-located with power plant: possible to reduce MBSP ~$45/ton, but logistical challenges for pond delivery

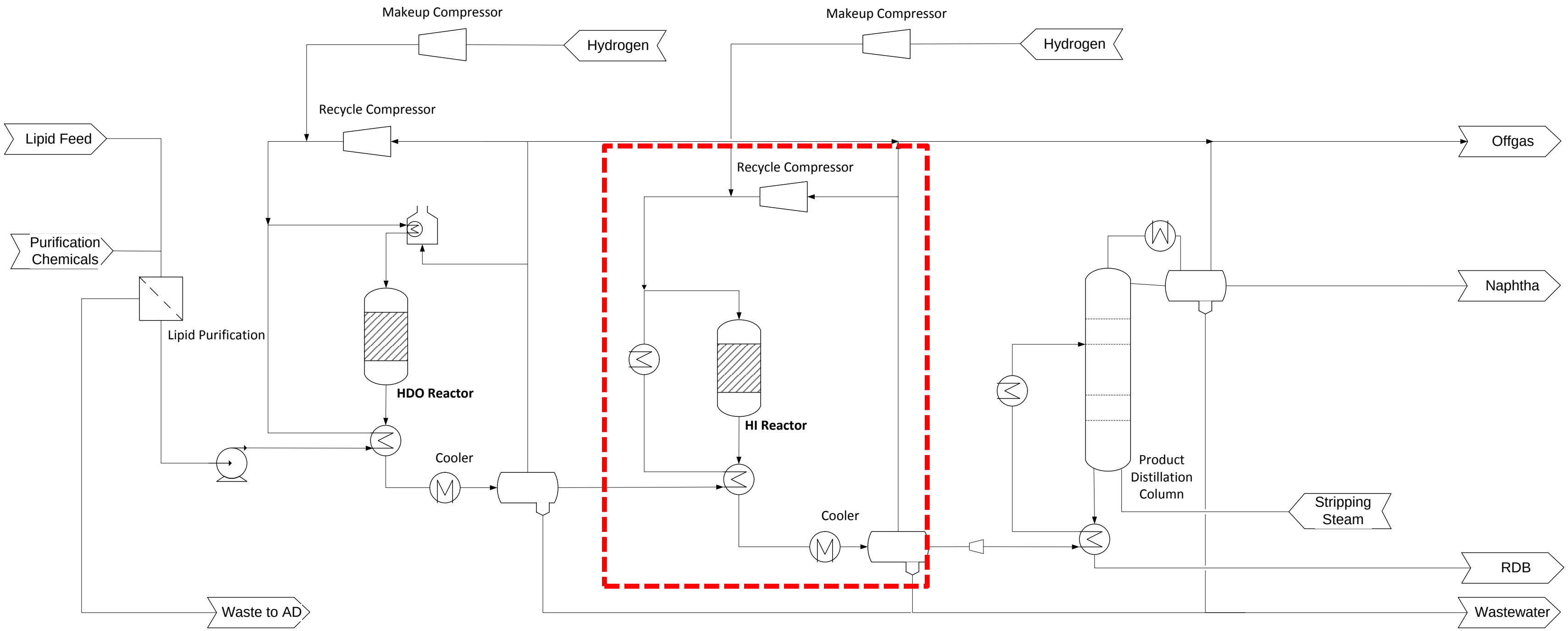
The $3/GGE Challenge for Algae



Algal biomass cost reductions and algal biomass value enhancements: Both are essential but neither is sufficient.

- Values shown on the right include original CAP (with ethanol) and HTL pathways; values in grey are extrapolated from MYPP costs
- Algae farm design report demonstrates that biomass costs below ~$450/ton will be very difficult
  - $3/GGE MFSP goals require <$230/ton biomass for both HTL + CAP (per 2016 MYPP)

Lipid Upgrading: HDO vs HI



- Prior work evaluated lipid upgrading to “blendstock” (HDO) versus “final fuel” (HDO+HI) product
- HDO – paraffinic product with high cetane, poor cloud point
- HI – isomerized product with improved cloud point
- Considered both cost premium (TEA) and “value addition” (NREL Blending Model) to add extra HI step

Lipid Upgrading: HDO vs HI

Blending Model Inputs				
	DO animal fat		DO+HI animal fat	
	Sample I		Sample E	
Diesel Properties	Value	Units	Value	Units
90% Vol. Dist. T	559.6	F	556.0	F
EP Vol. Dist. T	580.4	F	575.4	F
Aromatics	0.10	Vol %	0.30	Vol %
Sulfur	0.30	Wt ppm	0.40	Wt ppm
Specific Gravity	0.795	g/ml	0.777	g/ml
Flash Point	257.0	F	141.8	F
Viscosity @122 F	3.60	Cst	2.50	Cst
Pour Point	65.2	F	(12.2)	F
Cloud Point	75.2	F	(2.2)	F
Carbon Residue	-	Wt %	0.04	Wt %
Cetane Blend index	117.8		72.2	

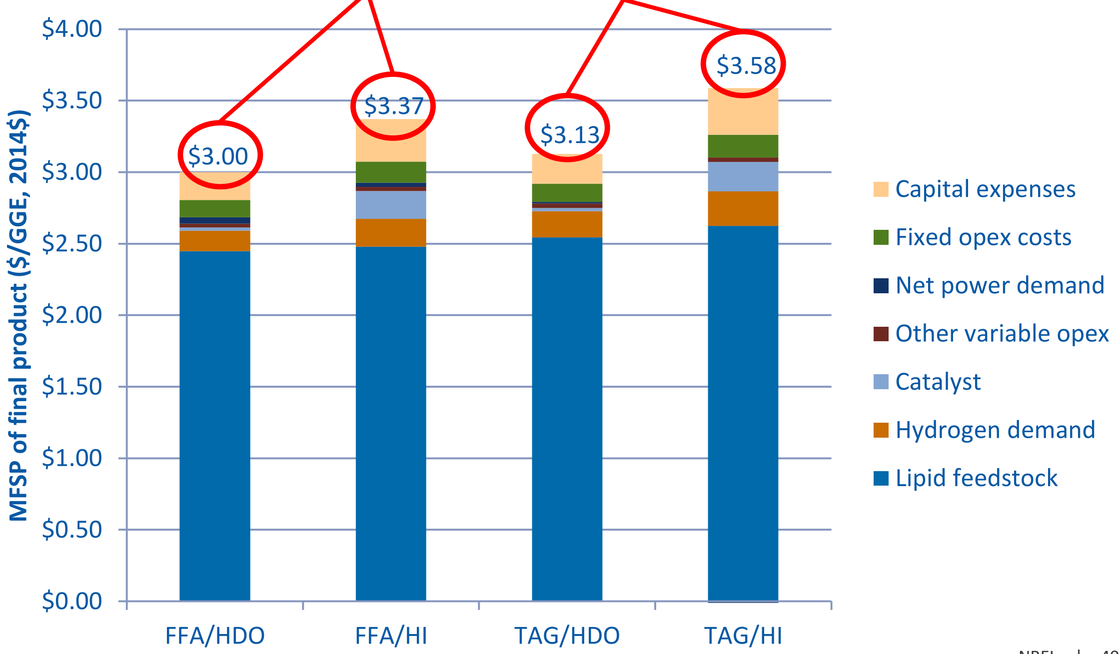
Smagala et al., *Energy & Fuels* 2013

Fuel / Blendstock Property		DO animal fat Sample I	DO+HI animal fat Sample E
Value of Bio-Blendstock ($ / Gal)	Minimum	1.53	2.96
	Average	2.74	2.96
	Maximum	2.97	2.97
Bio-Blendstock in Finished Diesel (Vol%)	Minimum	2.6%	100.0%
	Average	8.6%	100.0%
	Maximum	12.5%	100.0%
Constraining Properties		Pour Point Clound Point	None (Meets all specs)

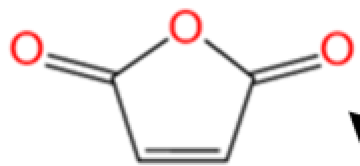
Δ value (blending model) = $0.22/gal

Δ cost (TEA) = $0.37 – $0.45/GGE

- Preliminary TEA based on experimental work for algae lipids (high-FFA), extrapolated to TAG lipids as additional case
- Current R&D is un-optimized for HI step (low LHSV, costly catalyst)
- TEA based on current R&D indicates not worth adding HI – adds more cost on TEA than expected value as a finished fuel
- However, potential future improvements may allow reducing cost premium below $0.22/gal

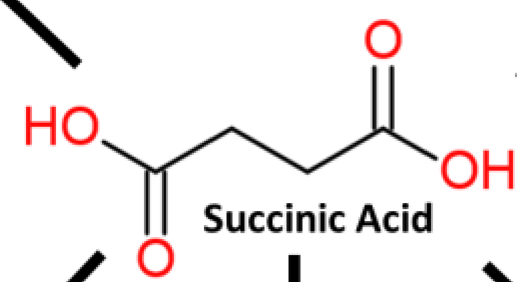


Succinic Acid



Maleic Anhydride

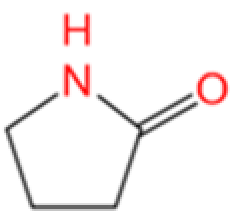
Global Demand: >1.5 MM tons
Expected Growth: 5%
Market Price: $1,400/ton
Primary Usage: Polyester resin, BDO, fumaric acid



Succinic Acid

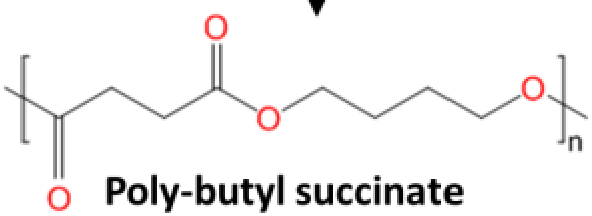
1,4 Butanediol

Global Demand: >1.5 MM tons
Expected Growth: 5%
Market Price: $1,600/ton
Primary Usage: Specialty chemicals



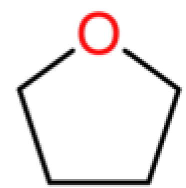
Pyrrolidinones

Global Demand: > 0.5 MM tons
Primary Usage: Specialty chemicals



Poly-butyl succinate

Global Demand: > 0.02 MM tons
Primary Usage: Polymers



Tetrahydrofuran (THF)

Global Demand: >0.8 MM tons
Expected Growth: 5%
Market Price: $2,800/ton
Primary Usage: Polymers, solvents

Adopted from: Biddy, Mary J., et al. "The techno-economic basis for coproduct manufacturing to enable hydrocarbon fuel production from lignocellulosic biomass." ACS Sustainable Chemistry & Engineering 4.6 (2016): 3196-3211. and Biddy, M. J., Scarlata, C., Kinchin, C., 2016 Chemicals from Biomass: A Market Assessment of Bioproducts with Near-Term Potential. Golden, CO: National Renewable Energy Laboratory. http://www.nrel.gov/docs/fy16osti/65509.pdf