NREL
NATIONAL RENEWABLE ENERGY LABORATORY





DOE Bioenergy Technologies Office (BETO) 2017 Project Peer Review

Algal Biofuels Techno-Economic Analysis

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National Renewable Energy Laboratory

Algae Platform Review, March 6, 2017, Denver, CO

Goal Statement

Goal:

•Provide **process design and economic analysis support** for the algae platform to **guide R&D priorities** to commercialization

- Translate demonstrated or proposed research advances into economics quantified as $/ton feedstock or $/gal fuel price

Outcomes:

•Project develops benchmark process models in Aspen Plus and related 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 the BETO Program 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

- Started: 2010
- Finish: 2019 (ongoing, 3-year cycle)
- Ongoing AOP Project (NA% complete)

Barriers

- MYPP Barriers addressed
  - AFt-A: Biomass Availability and Cost
    - *This project quantifies biomass + fuel costs*
  - AFt-H: Overall Integration and Scale-Up
    - *TEA models tie all R&D operations together*
  - AFt-I: Algal Feedstock Processing
    - *Our work strives to optimize processing/ maximize value*

Budget

	Total Costs FY 12–FY 14	FY 15 Costs	FY 16 Costs	Total Planned Funding (FY 17–Project End Date)
DOE-Funded	$660K	$350K	$300K	$900K
Project Cost Share (Comp.)	NA	NA	NA	NA

Partners

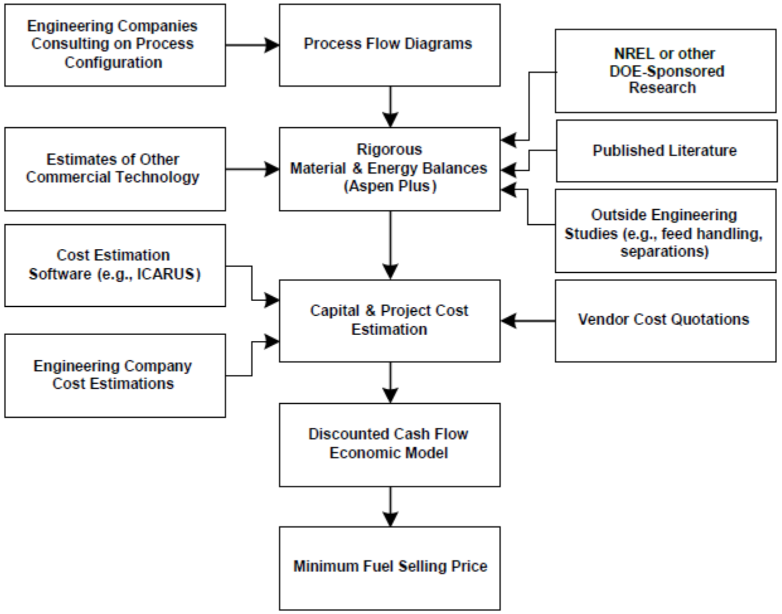
- No partners with shared funding
- Other interactions/collaborations
  - ANL–GREET LCA modeling team
  - PNNL–BAT RA modeling team, algal HTL modeling team
  - ORNL–Billion Ton modeling team
  - INL–Algal feedstock logistics team
  - Consortia–substantial interaction with ATP^3, Separations Consortium
  - Industrial partners
  - Engineering subcontractors

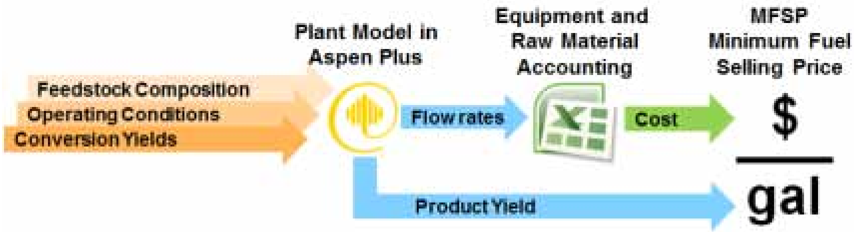
Project Overview

- This project has a 7-year 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
  - Design report on biomass cultivation/harvesting ("farm model") published in 2016
  - PBR study completed 2016 (paper in preparation)
- 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)

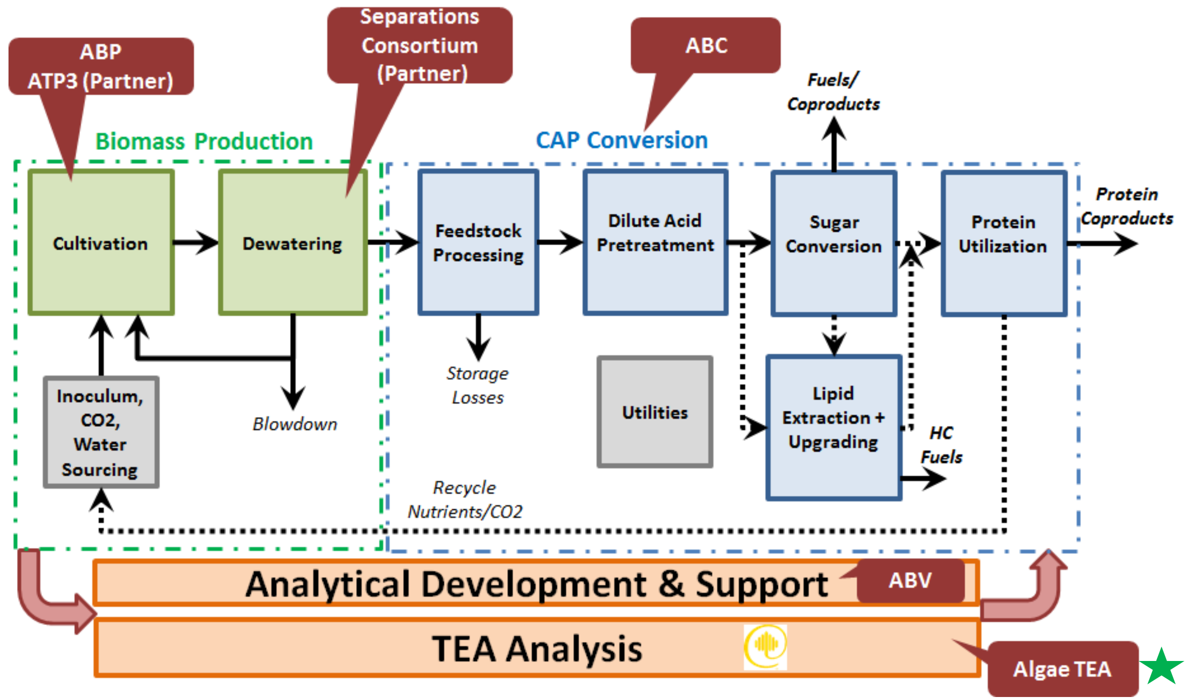
- Process models in Aspen Plus based on NREL/partner research data (where available), published literature (when necessary)
- Discounted cash-flow ROR calculation determines minimum fuel selling price (MFSP)
- Credibility of analysis supported by vendor-based cost estimates, thorough vetting with industry and research stakeholders
- **Critical success factors:**
  - Process models must be useful: Highlight barriers for scale-up/commercialization in under-researched areas, conduct sensitivity analysis to find biggest "bang for the buck" items for targeted improvement
  - Critical to maintain credible engineering analyses that are transparent and unbiased. Work with engineering subcontractors to reduce uncertainty, subject design reports to thorough external peer review
- **Challenges:**
  - Collecting meaningful data (large-scale, year-round, commercially relevant conditions) for cultivation requires significant resources–unique challenge for algae
  - Algal biofuels are strongly challenged by cost of biomass–**$3/GGE fuels require biomass cost improvements AND fundamental process shifts:** must leverage TEA early on to identify paths forward (balance modeling time vs rigor)





Approach (Management)

- Project management tracked using milestones
- Monthly platform meetings
- Outreach to external partners + industry
- Activities highly integrated with research efforts, assist in prioritizations for R&D
  - Example: TEA demonstrated potential MFSP benefits for the R&D to move to new coproducts (ABC/ABV)



Project Milestones/Activities	FY16				FY17				FY18 (planned)			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Upstream process focus (biomass production logistics)												
Coproduct opportunities for $3/GGE algal fuels	▼	●									●	
Lipid upgrading analysis			▼									
Biomass valorization (growth versus compositional value)						▼				▲		
SOT benchmarking				▲				▲				▲
Downstream process focus (biomass conversion to fuels)												
Harmonization modeling (with ANL, PNNL, ORNL)				▼	▼			▲				
PBR cultivation TEA assessment				▲								
Wet algal biomass storage logistics TEA							▼					
SOT benchmarking				▲				▲				▲

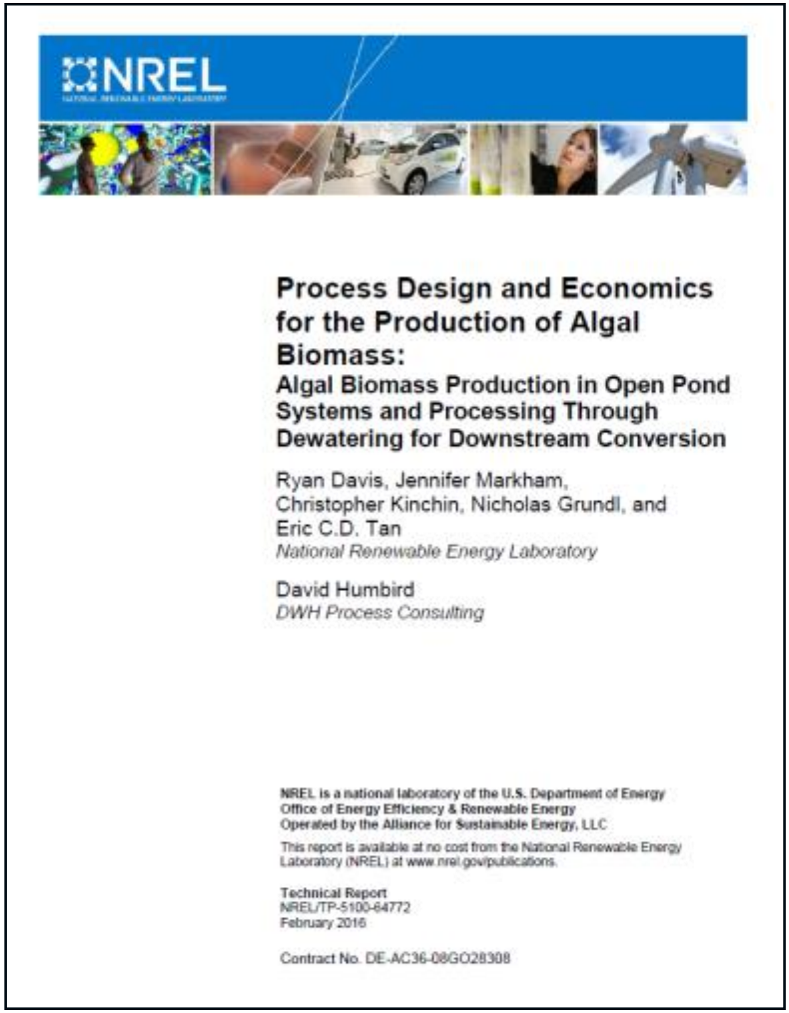
▲ = Milestone ▼ = Quarterly progress measure ● = Go/no-go decision

Technical Accomplishments/Progress/Results:
2015 Algal Biomass Design Report

- Project goals to be achieved by 2022 and corresponding economics for algae "farming"
  - Focused on open pond cultivation
    - PBR case completed late FY16
  - Primary value to public domain is the **use of four independent but credible sources for design and cost details** for pond systems (key step of process)
  - <u>*This approach shows significantly better agreement*</u> on what commercial pond systems should "actually" cost than typical statements made publicly
  - Report was leveraged for MYPP and in forming the basis of ISBL costs for new Billion Ton – Algae chapter

- Beyond base case, numerous sensitivity scenarios considered
  - CO_2 vs. flue gas
  - Lined vs. unlined ponds
  - Productivity vs. cost
  - Alternative strains

- Two approaches for analysis
  1) "Top-down": What does performance + cost "need to be" to hit any given biomass cost goal?
  2) "Bottom-up": TEA for a base case set of inputs


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

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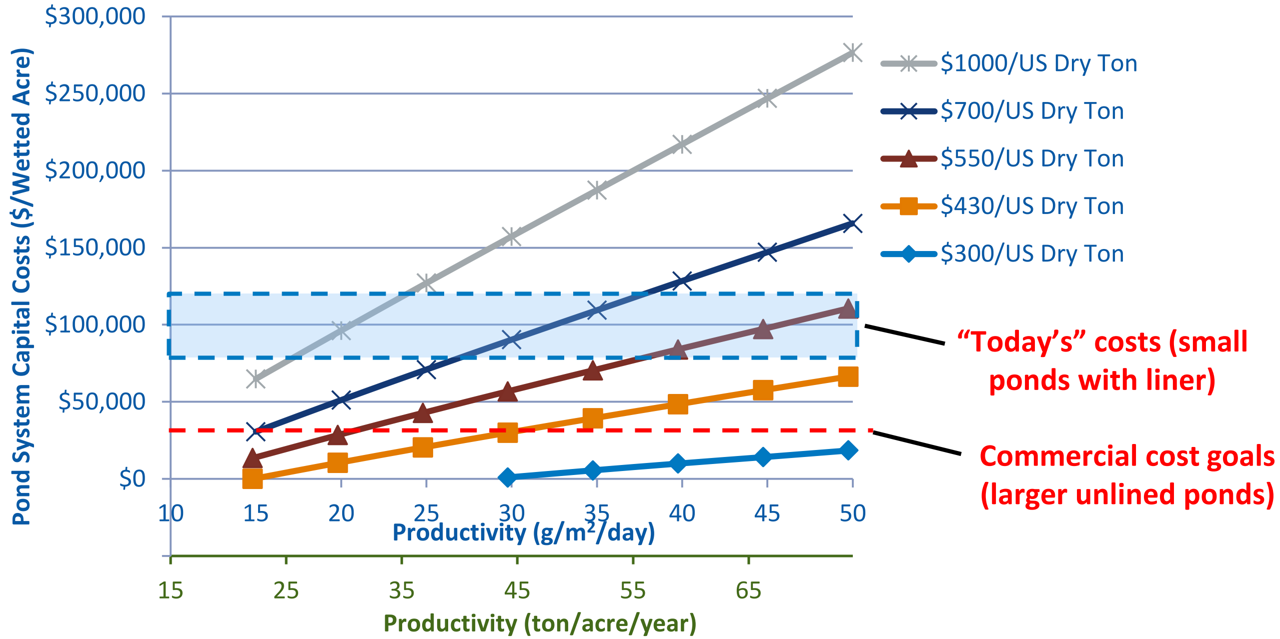
Technical Report
NREL/TP-5100-64772
February 2016

Contract No. DE-AC36-08GO28308

http://www.nrel.gov/docs/fy16osti/64772.pdf

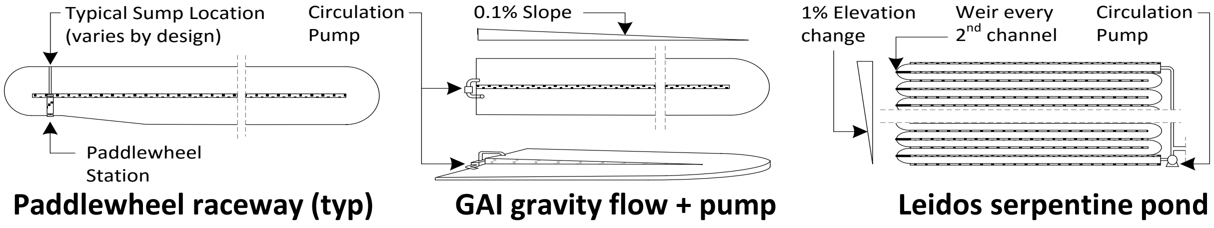
“Top-Down” Analysis – MBSP Dependencies on Pond Costs + Productivity



- Y and X axes – mutually independent variables
- Contours = resulting minimum biomass selling price (MBSP)
- MBSP reduces for higher productivity or lower pond cost
- Likely lower limit for system costs ~$30K/acre (commercial nth plant)
  - At this limit $430/ton is possible (@ 30 g/m^2/day), but challenging to reduce costs any further
  - **Even if ponds were “free,” CO_2/nutrient/other costs still add up to $300–$400/ton lower boundary**

"Bottom-Up" Analysis – Economy of Scale Advantages for Pond Designs

NREL solicited 4 separate inputs on 8 pond designs/costs

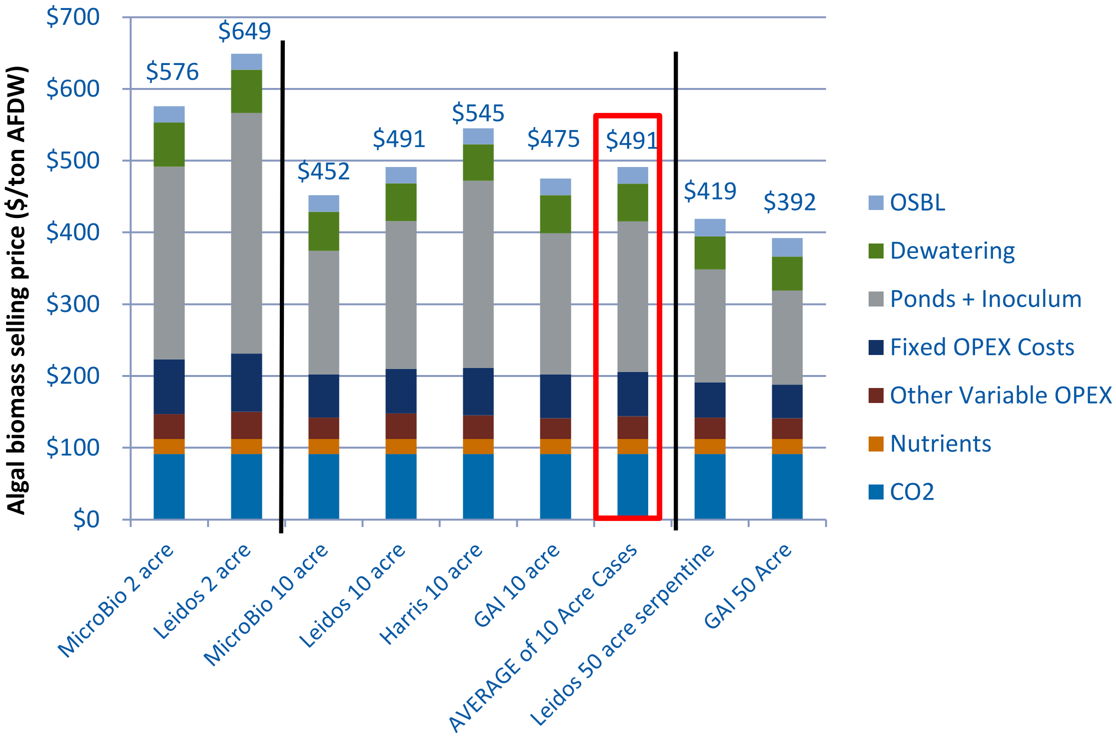


Source	2 acre	10 acre	50 acre
Leidos (engineering firm)	R	R	S
MicroBio (expert consultants)	R	R	
Harris Group (engineering firm)		R	
GAI (commercial developer)		G	G

R = paddlewheel raceway

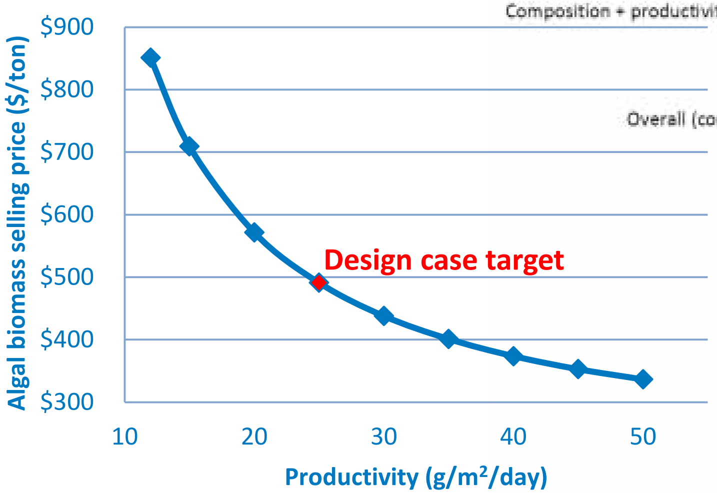
S = gravity-flow serpentine

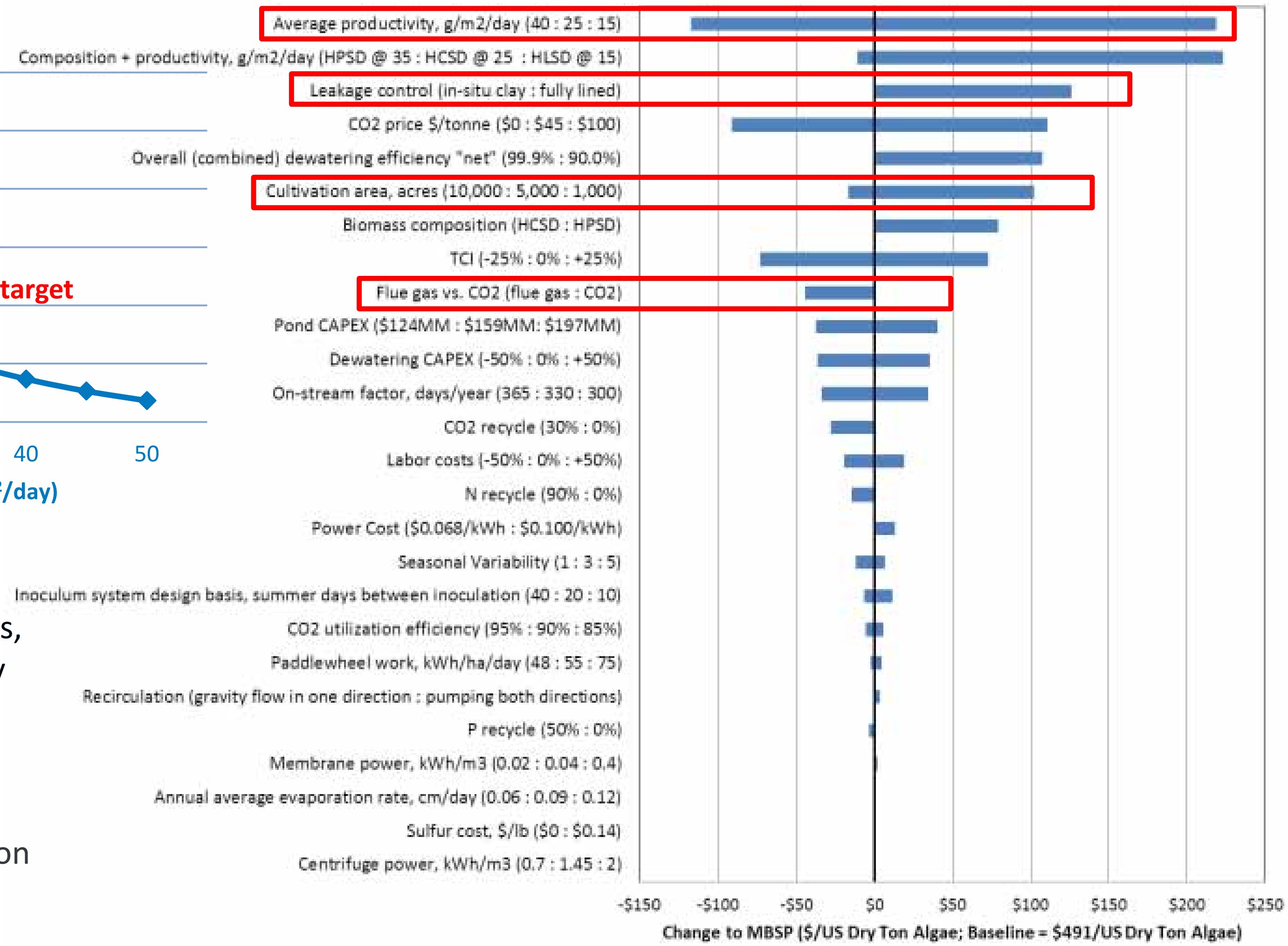
G = GAI design (gravity raceway with pump)



- TEA model considered 5,000-acre farm including ponds, inoculum, CO_2 sourcing, dewatering to 20% solids, circulation pipelines
- 25 g/m^2/day target productivity
- **Good agreement between sources for pond costs of a given size** (drives MBSP); differences mainly a function of pond size
- **Strong economy of scale advantages for pond design:** $122/ton average premium for 2- vs. 10-acre ponds
- $85/ton savings to move from 10- to 50-acre ponds, but becomes more speculative at such large scales
- For purposes of selecting a single MBSP value, average of the four 10-acre cases was used (~$32k/acre pond system costs)

Sensitivity Analysis–Productivity Drives TEA





Key drivers:

- Productivity: dictates economics, critical to achieve $\geq$25 g/m^2/day
- Liners: adding full pond liners = $\geq$\$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 = $\pm$\$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

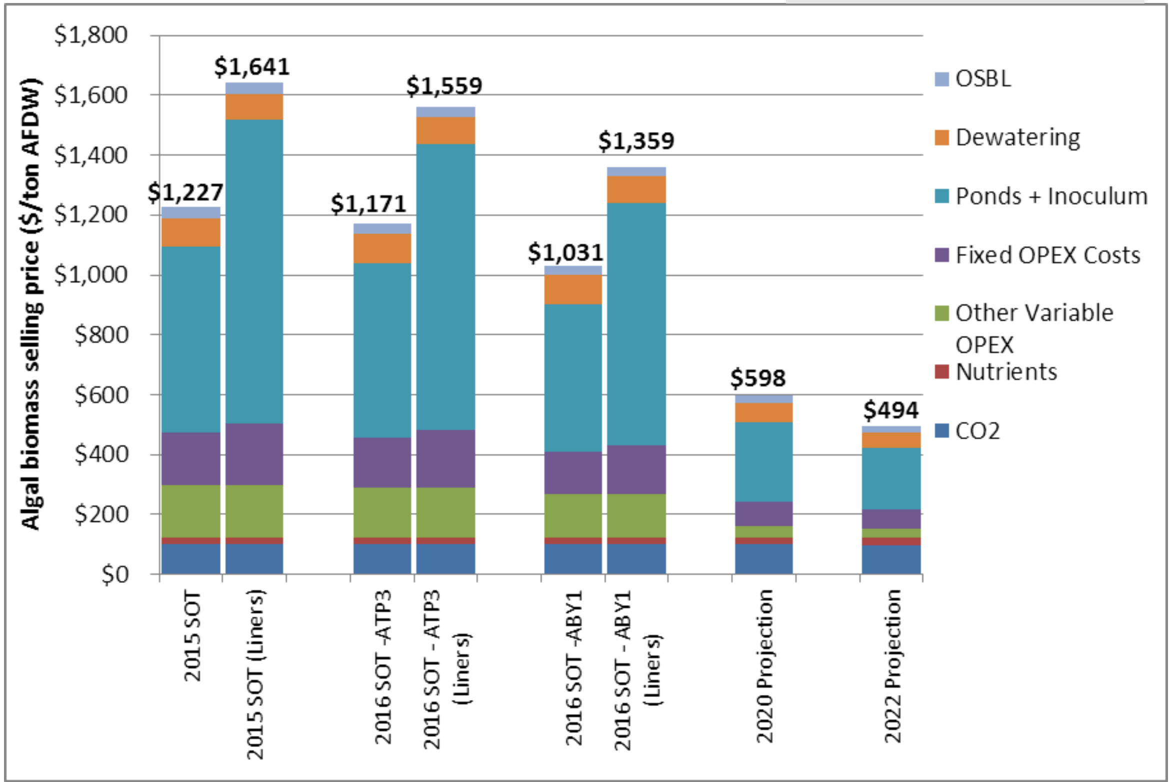
Technical Accomplishments/Progress/Results: *NREL TEA Sets SOT Benchmarks*

Season	2015 SOT (ATP³)	2016 SOT (ATP³)	2016 SOT (ABY1 Performer)	2020 Projection	2022 Design Case
Summer	10.9	13.3	17.5	27.4	35.0
Spring	11.4	11.1	13.0	22.9	28.5
Fall	6.8	7.0	7.8	19.6	24.9
Winter	5.0	5.0	4.8	9.1	11.7
Average	**8.5**	**9.1**	**10.8**	**19.7**	**25.0**
Max variability	**2.3:1**	**2.7:1**	**3.6:1**	**3:1**	**3:1**
MBSP ($/ton, 2014$)	**$1,227**	**$1,171**	**$1,031**	**$598**	**$494**

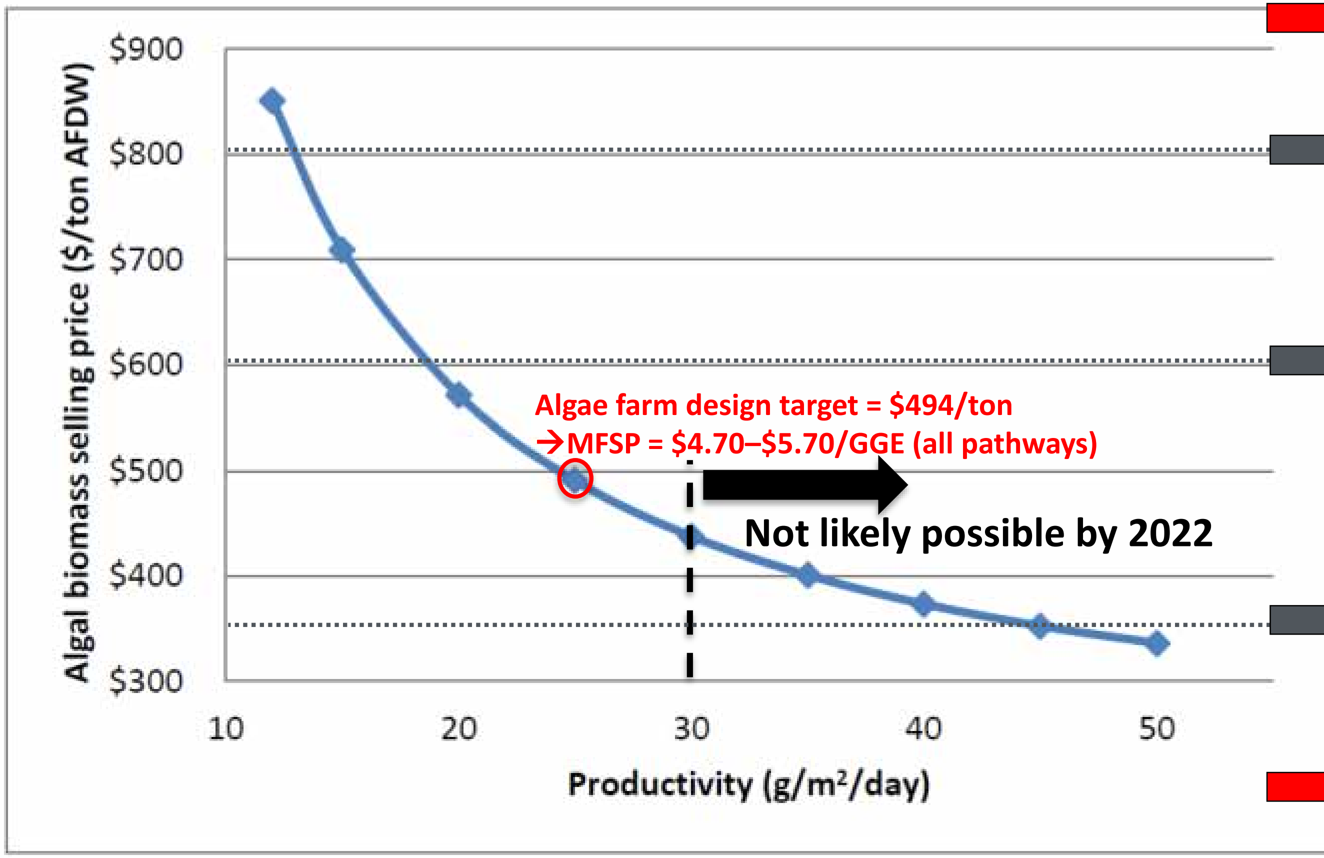

NREL ATP³ Algae Testbed
Use of Cultivation Data from the Algae Testbed Public Private Partnership as Utilized in NREL's Algae State of Technology Assessments
Eric Knoshaug, Lieve Laurens, Christopher Kinchin, and Ryan Davis
National Renewable Energy Laboratory
Golden, Colorado

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

- Biomass SOT cases began in 2015–2016
- Primary cultivation data furnished by ATP³ – supplemented by ABY1 industry performer in 2016
- 2016 ATP³ productivity improved by 7% due to switch to strain rotation strategy



The $3/GGE Challenge for Algae



2016 SOT = $1,171/ton
MFSP = $12.80–$19.70/GGE

$800/ton:
MFSP = $6.70–$8.50/GGE

$600/ton:
MFSP = $5.40–$6.80/GGE

$350/ton:
MFSP = $3.80–$4.70/GGE

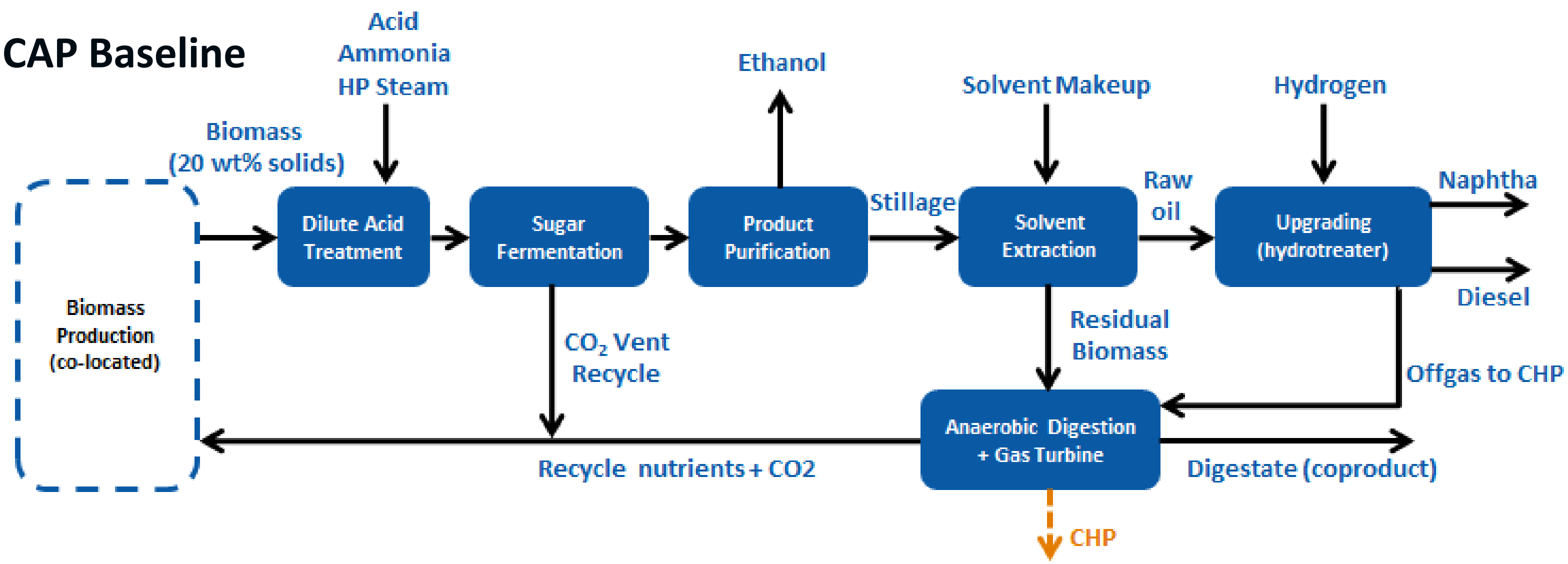
$3/GGE requires
$160–$230/ton biomass cost
→Not possible in base farm model

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 MYPP)

Technical Accomplishments/Progress/Results:
Paths to $3/GGE – Coproducts Drive Down MFSP

CAP Baseline



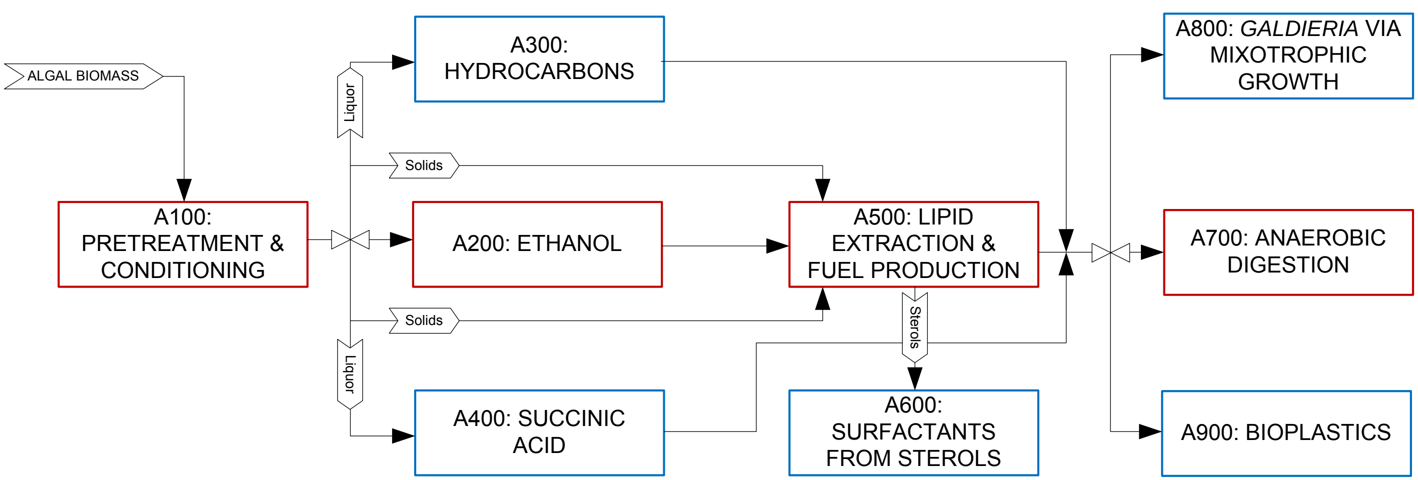
Best case >$5/GGE MFSP

Alternative Options

Sugar Conversion Processes

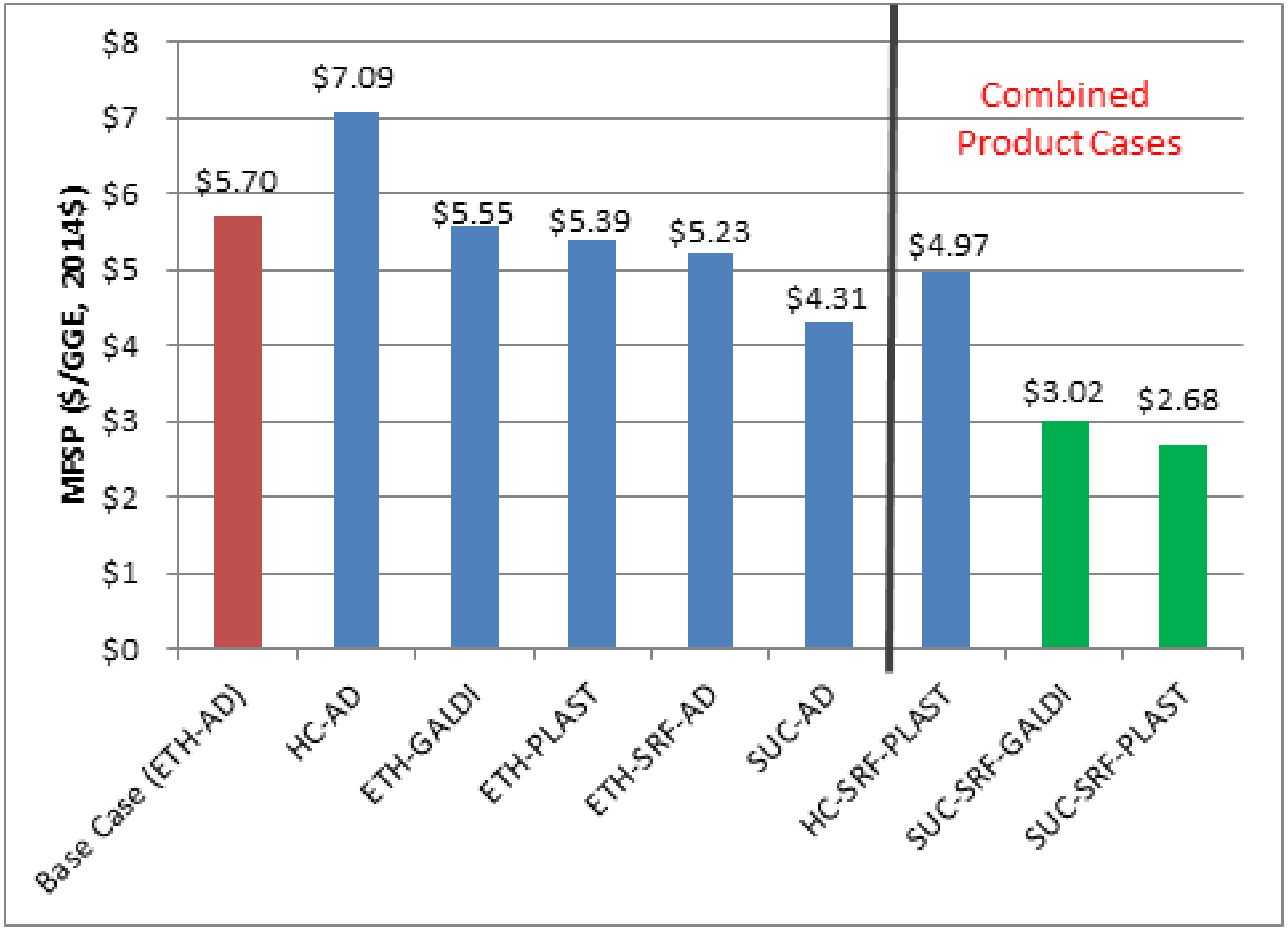
Lipid Conversion Processes

Protein Conversion Processes



Evaluate alternative coproducts (individually and in combination)

TEA Results – High-Value/High-Volume Coproducts Are Key to $3/GGE



ETH – Ethanol

AD – Anaerobic Digestion

GALDI – Mixotrophic *Galdieria* biomass

PLAST – Bioplastic

SRF – Sterol-derived surfactants

SUC – Succinic acid

**All cases constrained to biomass cost + composition per algae farm design report*

- Two cases achieved $3/GGE goals at algae farm biomass targets (both require multiple coproducts): succinic acid + surfactants + *Galdieria* or plastics
- **High-value/high-yield coproduct is key to achieving $3/GGE**
- These findings guided the NREL ABC project to begin exploring succinic acid in FY16
- Additional options also possible (for example protein fermentation → C4+ alcohols, SNL)

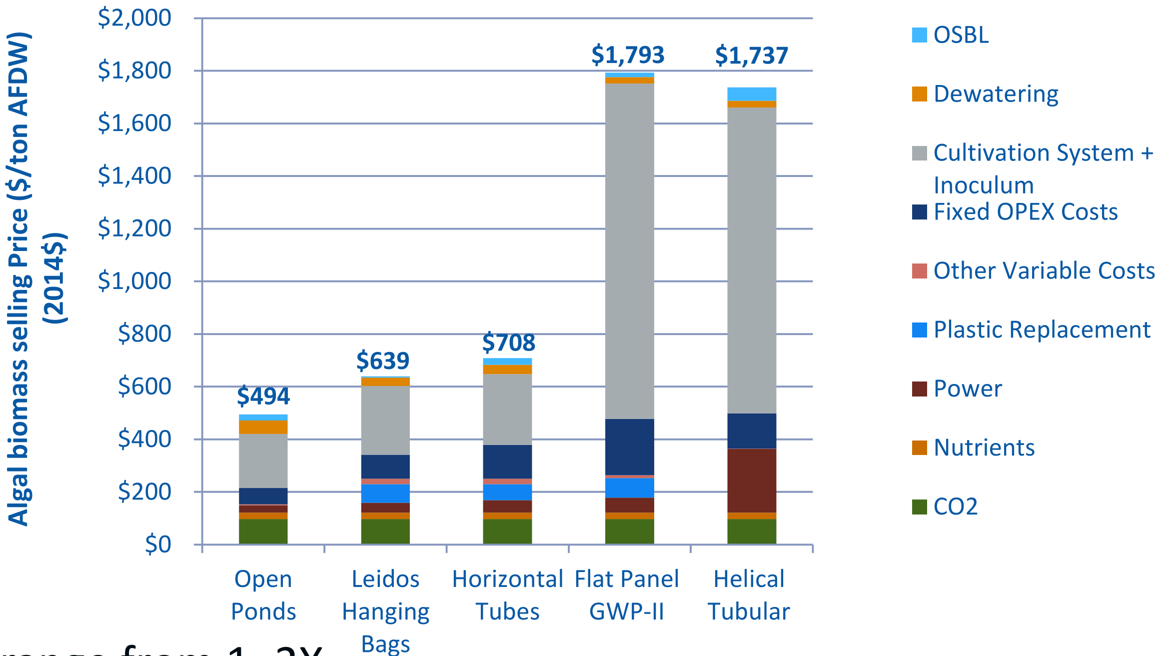
Technical Accomplishments/Progress/Results:
CAP Conversion SOT – Lower Cost Biomass, Higher Value Product

Metric	2015 SOT (EtOH-AD)	2016 SOT - ATP3 (SA-AD)	2016 ABY1 (SA-AD)	2022 Projection (EtOH GGE-AD)	2022 Projection (SA-SRF-GALDI)	2022 Projection (SA-SRF-PLAST)
Minimum Fuel Selling Price ($/GGE, 2014$)	$20.56	$19.18	$16.77	$5.48	$3.02	$2.68
Conversion Contribution ($/GGE, 2014$)	$1.52	$0.74	$0.54	$1.28	($4.14)	($4.48)
Yield (GGE/ton afdw)	103	64		117	70	
RDB Yield (GGE/ton afdw)	49	49		54	68	
Naphtha Yield (AFDW algae basis)	15	15		16	2	
Ethanol Yield (AFDW algae basis)	39	N/A		47	N/A	
C Efficiency from Biomass in Fuels/SA/Others (%)	48.8/NA/14.1	30.3/16.3/16.0		55.5/NA/11.4	33.1/23.4/41.0	
Feedstock						
Feedstock Cost ($/ton afdw)	$1,227	$1,171	$1,031	$494		
Year-Average Cultivation Productivity (g/m^2/day afdw)	8.5	9.1	10.7	25		
Feedstock Lipid/Carb/Protein Content[e]	27%/51%/13%	27%/51%/13%		27%/51%/13%		
Pretreatment						
Pretreatment Solids Loading (wt%)	18-25%	20%		20%		
Acid Loading (wt% verses feed water rate)	2%	2%		1%		
Fermentable Sugar Release ("glucose yield")	74%	74%		90%		
Glucan to Degradation Products	1.5%	1.5%		0.30%		
Hydrolysate solid-liquid separation	No	Yes		No	Yes	
Sugar Processing						
Fermentation Batch Time (hr)	<18	N/A		<18	N/A	
Fermentation Total Solids Loading (wt%)	20%	N/A		20%	N/A	
Fermentable Sugar Utilization (%)	98.50%	N/A		98.50%	N/A	
SA glucose/mannose utilization (%)	N/A	98.6/86	98.6/86	N/A	99.4/99.4	99.4/99.4
SA productivity (g SA/L/hr)	N/A	0.6	0.6	N/A	2	2
Lipid Recovery & Processing						
Extraction Solvent Loading (g/g solvent/dry biomass)	5.9	5.9	5.9	5	5	5
FAME Lipid Extraction Yield (%)	87%	87%	87%	95%	95%	95%
Polar Lipid Impurity Partition to Extract (%)	<11.5%	<11.5%	<11.5%	<11.5%	33%	33%
Surfactant yield (g Surfactant/g Sterol)	N/A			N/A	1.96	1.96
Hydrotreating						
Hydrotreating RDB Yield (wt% of oil feed)	64%	64%	64%	64%	83%	83%
Hydrotreating Naphtha Yield (wt% of oil feed)	19%	19%	19%	19%	2%	2%
Hydrotreating H_2 Consumption (wt% of oil feed)	2.6%	2.6%	2.6%	2.6%	2%	2%
Protein/Residual Processing						
Bioplastic yield (g bioplastic/ g processed solids)	N/A			N/A		1.69
Galdieria yield (mixotrophic) (g Galdieria/g TOC)	N/A			N/A	2.5	N/A

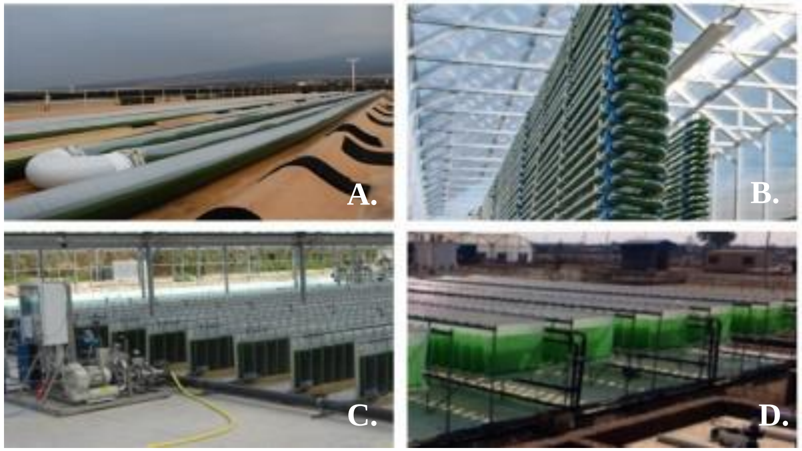
- FY16 CAP SOT = $19.18/GGE for ATP[3] data and $16.77/GGE for ABY1 data
- ~$1.4/GGE improvement moving from ethanol (FY15) to SA (FY16)
- Significant room for further improvement on biomass cost, introduction and optimization of more coproducts

Technical Accomplishments/Progress/Results: *PBR Study – Tradeoffs in System Costs vs Productivity*

- PBR study completed in late FY16
- Similar approach to open pond design report: solicited inputs from four experts developing PBR systems
- Productivity curves from literature, PNNL BAT team



- Future productivity projections range from 1–2X higher than ponds (design-specific)
- MBSP 1.3–3.6X higher for PBRs vs. ponds
  - **However, more uncertainties behind PBR inputs, and likely a "heavier lift" for ponds to achieve nth-plant goals (e.g., 330 day/year uptime)
- Significant variation in cost + lifetime between PBR designs leads to 3-fold difference in MBSP estimates
- Beyond biofuels, PBRs are important in cases requiring compositional control, high-value products, nutraceuticals, etc.

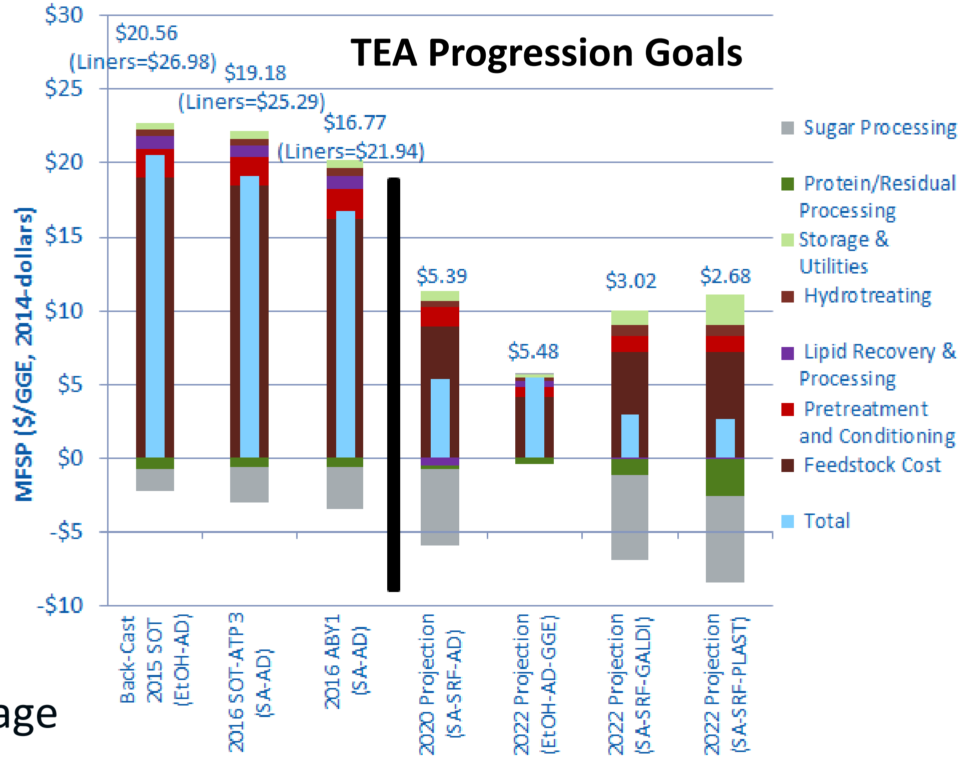


A – Horizontal Tubes B – Helical Tubes
C – Flat Panel GWP-II D – Leidos Hanging Bags

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 (forms basis for BETO MYPP goals)
- Identifies key R&D directions (pathways, coproduct opportunities, etc.)
- Analysis can serve many stakeholders
  - Industry (facilitate interaction between industry, NREL, DOE)
    - *Example: Outreach to Clearas Water for TEA*
  - Research community, decision makers



- This project supports BETO's efforts to encourage collaboration across multiple organizations:
  - Continued interactions with **harmonization partners** (ANL–LCA, PNNL–BAT, TEA teams, ORNL–CO_2)
  - Interactions with consortia:
    - **ATP3:** TEA modeling support for test-bed sites across U.S., leveraging data to inform SOT and future target cultivation metrics/costs
    - **Separations Consortium:** TEA support for algal dewatering research

2016 MYPP Critical Emphasis Area:
Prioritizing Algal R&D Barriers:
*"**Performing integrative analysis to identify critical barriers** and evaluate impacts on overall yield to developments in biology, cultivation, and processing."*

Future Work

- FY17 Harmonization:
  - Regroup with harmonization partners (ANL, PNNL, ORNL) to update models and conduct new harmonization – *Q4 FY17 (joint with ANL, PNNL, ORNL)*
  - Key focus of work will be to **evaluate future potential for algal biofuels on a national scale, given constraints imposed by TEA, LCA, and resource availability**
  - Work will consider saline vs. fresh water, CO_2 sourcing, requirement for liners, and max farm size
- Biomass growth versus composition assessment:
  - Evaluate trade-offs between productivity vs. composition on resultant “intrinsic value” of biomass for CAP pathway to fuels/products – *Q2 FY17, Q2 FY18 (joint with ABV)*
- Algae feedstock logistics:
  - TEA modeling on wet storage options for dewatered biomass – *Q3 FY17 (joint with INL)*
- SOT benchmarking (biomass production + CAP conversion) – *Q4 FY17, 18*
- National-scale coproducts assessment and design report:
  - Demonstrate potential for $\geq$1 BGY national-scale fuel production at a modeled MFSP of $3/GGE with coproducts at yields below market saturation limits – ***Q3 FY18 Go/No-Go***
  - **Establish new design report** documenting CAP pathway strategy for $3/GGE algal biofuels with applicability for national-scale fuel production alongside high-value coproducts – *Q1-2 FY19*
- TEA support for ATP^3:
  - Update TEA models for ATP^3 across all testbed sites based on latest cultivation data – *Q2-3 FY17*

Summary

- This project supports industry and research community via design reports, communication with stakeholders, and external collaborations
- TEA work is highly relevant to supporting program directions for BETO, near- and long-term R&D for NREL and partners
- NREL algae TEA project has made important achievements since 2015 peer review
  - Established a new algae farm design report, projecting cultivation improvements and biomass cost goals by 2022
  - Highlighted challenges toward achievement of $3/GGE and guided R&D transition toward coproducts in CAP

    → *MFSP goals require high cultivation productivity, suitable compositions*
  - Established new SOT benchmarks for biomass production and CAP conversion for both ethanol (2015) and succinic acid (2016)
  - Completed PBR study, TEA manuscript in preparation
- Further efforts moving forward may focus on novel low-cost cultivation systems or wastewater scenarios to further reduce biomass production costs

NREL, Sept, 2010, Pic #18229

Additional Slides

www.nrel.gov

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Responses to Previous Reviewers' Comments from 2015 Review

- An over-arching problem, which they do not control, is the lack of realistic production data. Hopefully, future work with the test-beds and industry collaboration will assist with this.
- We agree that data availability is a key challenge for this project, particularly as it relates to state of technology (SOT) benchmarking efforts. Cost of algal biomass is by far the largest driver on overall fuel costs, thus is a key metric to quantify through SOT updates in leading up to future demonstration of biomass cost targets <$500/ton (tied to productivity $\geq$ 25 $g/m^2/day$). However, collection of real-world cultivation data conducted over a long-term at a meaningful scale requires significant resources and long time commitments which few organizations have the capacity to support, particularly who are willing to share such data for public use. Since 2015, this challenge has begun to improve, with large datasets spanning two years of cultivation efforts released by the ATP^3 test-bed consortium (available at http://en.openei.org/wiki/ATP3), with whom we are a partner, which enabled establishment of algae SOTs for the first time in 2015-2016. Additionally, the 2016 SOT update also included a secondary case based on cultivation data furnished by an industry performer under BETO's ABY1 FOA, also with whom we are a partner, with a manuscript planned to be published later in 2017.

- Some people take these analyses as conclusive. Issues surrounding CO_2 delivery and nutrient recycling may radically alter the benefits of different processes.
- We agree, and fully recognize the challenges/uncertainties that remain regarding CO_2 and nutrient sourcing, availability, and cost (all of which depend on the degree of recycling for these components from back-end conversion operations). We examined CO_2 sourcing strategies for a hypothetical large commercial algae farm in our recent 2016 "algae farm" design report, and this project also supported ORNL's 2016 Billion Ton – Algae analysis (which placed a large focus on CO_2 sourcing). Those recent efforts have begun to better address this challenge, and moving forward we plan to focus on this as a key metric in our upcoming 2017 Algae Harmonization initiative in collaboration with PNNL, ANL, and ORNL. At the same time, we continue focusing on CO_2 and nutrient recycling as key parameters to track and quantify in our back-end conversion pathway models.

Publications, Patents, Presentations, Awards, and Commercialization

Publications (since 2015 review):

- R. Davis, J. Markham, C. Kinchin, N. Grundl, E.C.D. Tan, D. Humbird, "Process design and economics for the production of algal biomass: Algal biomass production in open pond systems and processing through dewatering for downstream conversion." NREL Technical Report NREL/TP-5100-64772, February 2016; http://www.nrel.gov/docs/fy16osti/64772.pdf
- U.S. DOE (R. Davis, contributor to Chapter 7), "2016 Billion-Ton Report: Advancing domestic resources for a thriving bioeconomy – Chapter 7: Microalgae." ORNL/TM-2016/160, July 2016; https://energy.gov/sites/prod/files/2016/12/f34/2016_billion_ton_report_12.2.16_0.pdf
- E. Knoshaug, L. Laurens, C. Kinchin, R. Davis, "Use of cultivation data from the Algae Testbed Public Private Partnership as utilized in NREL's algae state of technology assessments." NREL Technical Report NREL/TP-5100-67289, October 2016; http://www.nrel.gov/docs/fy17osti/67289.pdf
- J. Markham, L. Tao, R. Davis, N. Voulis, L.T. Angenent, J. Ungerer, J. Yu, "Techno-economic analysis of a conceptual biofuel production process from bioethylene produced by photosynthetic recombinant cyanobacteria." *Green Chemistry* 18: p. 6266-6281, 2016
- E. Frank, A. Pegallapati, R. Davis, J. Markham, A. Coleman, S. Jones, M. Wigmosta, Y. Zhu, "Life-cycle analysis of energy use, greenhouse gas emissions, and water consumption in the 2016 MYPP algal biofuel scenarios." ANL/ESD-16/11, June 2016; http://www.ipd.anl.gov/anlpubs/2016/07/128907.pdf
- T. Dong, E.P. Knoshaug, R. Davis, L.M.L. Laurens, S. Van Wychen, P.T. Pienkos, N. Nagle, "Combined Algal Processing: A novel integrated biorefinery process to produce algal biofuels and bioproducts." *Algal Research* 19: p. 316-323, 2016

Presentations (since 2015 review):

- R. Davis, J. Markham, C. Kinchin, N. Grundl, "Techno-economic analysis for the production of algal biomass: Process, design, and cost considerations for future commercial algae farms." Presented at the Algae Biomass Summit, Phoenix, AZ, October 2016
- C.M. Kinchin, E.P. Knoshaug, J.N. Markham, L.M.L. Laurens, R.E. Davis, P.T. Pienkos, "Techno-economic analysis of algal biofuel production based on data from the Algae Testbed Public Private Partnership (ATP3)." Poster presentation at the Algae Biomass Summit, Washington D.C., October 2015

Backup Slides

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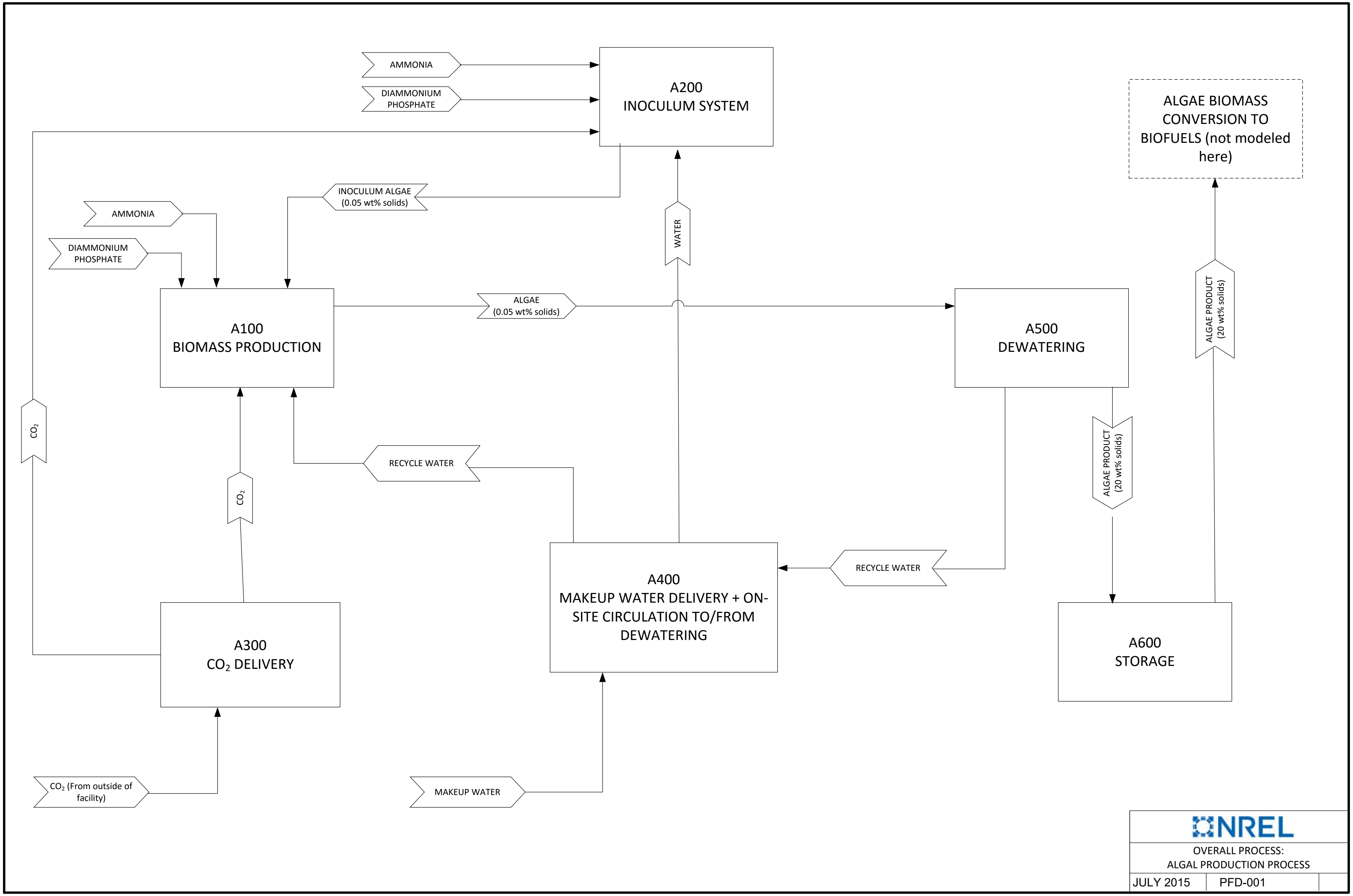
Algae Farm Design Report: Process Schematic



Algae Farm Design Report: Process Considerations

Metric	Summer	Fall	Winter	Spring	Annual Average
Biomass Productivity ($g/m^2/day$ AFDW)	35.0	24.9	11.7	28.5	**25**
Productivity Variance versus Summer Peak	NA (1:1)	1.4:1	3.0:1	1.2:1	**NA**
Pond Evaporation (cm/day)	0.090	0.035	0.035	0.189	**0.087**
Blowdown (MM L/day)	7.3	2.8	2.7	12.4	**6.3**

2022 goals:

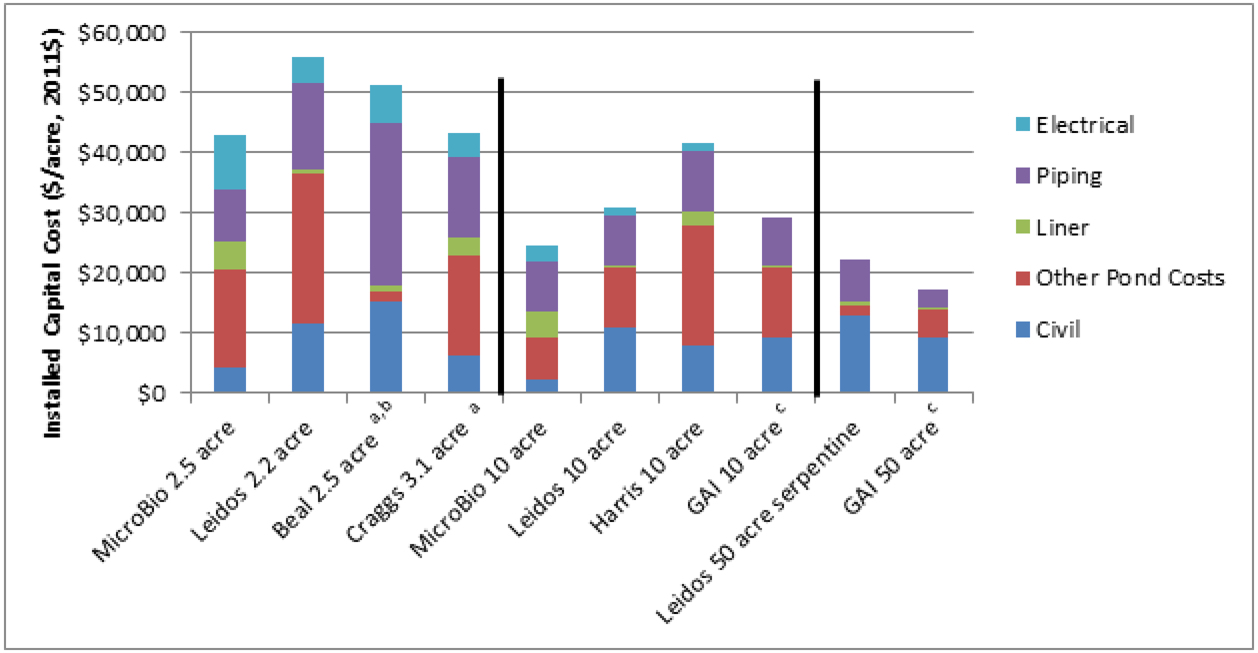
- Productivity: targeting 25 $g/m^2/day$ (AFDW annual avg)
  - External reviewer agreement that $\geq$25 *is or must be achievable* by 2022 to demonstrate sufficient progress over today's benchmarks
  - Best performance published to date = 23 $g/m^2/day$ (+ 40% lipids) (Huntley/Cellana), 8-21 $g/m^2/day$ April-October (White/Sapphire)

- Composition: mid-harvest/high-carbohydrate *Scenedesmus* (HCSD), 27% FAME lipids
  - *Scenedesmus* selected given detailed compositional data, commercial relevance
  - Composition + productivity = ~3.9% PE to biomass (from full-spectrum irradiance), vs ~14% max

- Seasonal variability: 3:1 (max vs min seasonal growth)
  - Key challenge unique to algae – adds design constraints for downstream conversion facility
  - Most recent basis from PNNL BAT model = ~5:1 average for Gulf Coast
  - May be reduced either through strain engineering or seasonal strain rotation
  - Current ATP3 data ~3-4:1 average of all sites, <2.5:1 for Florida ("representative" Gulf Coast site)

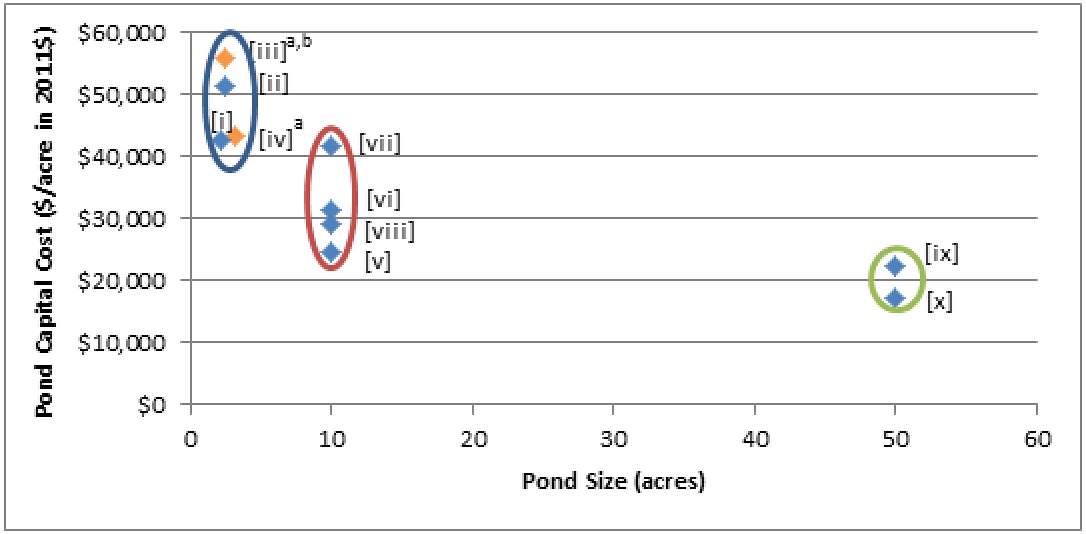
- Evaporation: Based on prior harmonization modeling work (Gulf Coast average)

Pond Cost Estimates



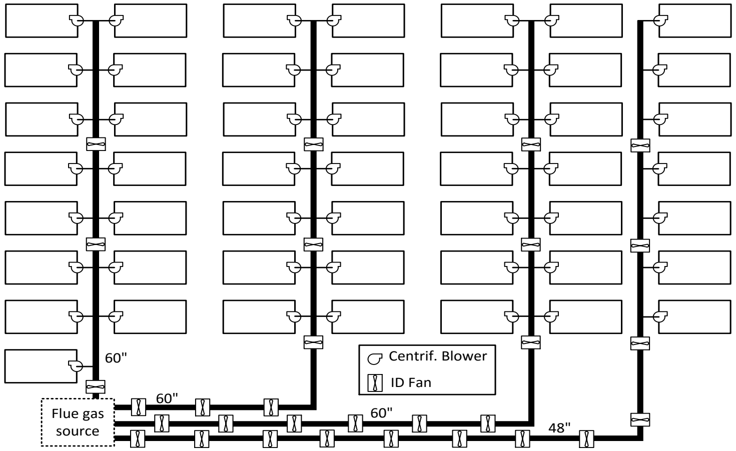
[a] Additional data points (not included in full TEA) added to this plot to further demonstrate cost alignment by pond size.
[b] Beal costs based on extrapolating from published costs for fully lined pond to a minimally-lined design. If a fully lined pond were used for the Beal case, total installed cost would be $114,000/acre.
[c] GAI cases include electrical costs under "other pond costs".

- Pond costs show reasonable agreement based on "small", "medium", or "large" size groupings
- More strongly a function of scale – highlights economy of scale advantages for building larger ponds >2-3 acres
- Largest cost drivers = paddlewheels + concrete ("other" category), piping, civil
  - Economies of scale are possible for piping (individual feed/harvest lines), paddlewheels, electrical
  - No notable scale advantages for civil

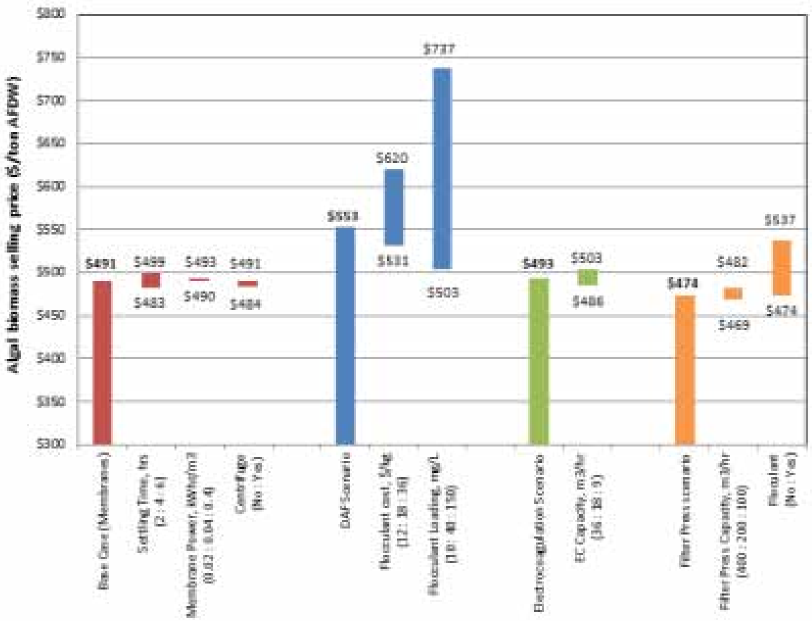


Algae Farm Design Report: Additional Sensitivity Scenarios

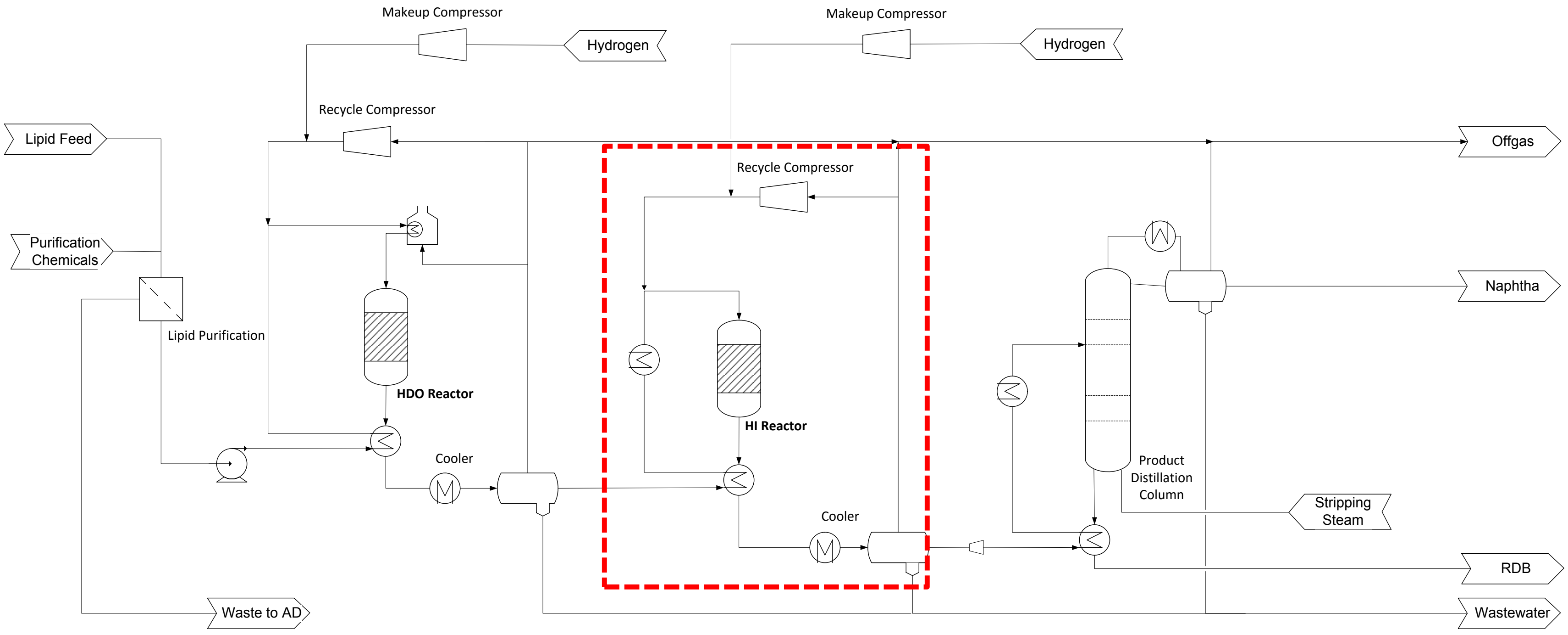
- CO_2: carbon capture vs bulk flue gas
  - Bulk flue gas pipeline 15 km from source: *requires more power to transport the needed CO_2 rate than the power generated to produce that amount of CO_2* – Also translates to ~$49/tonne (vs $45/tonne target for purified CO_2)
  - Flue gas co-location with algae facility (no significant off-site transport): $447/ton (~$45/ton MBSP savings) – But significant logistical/practicality questions regarding the use of multiple large ductwork pipelines routed around facility
- Alternative strains
  - Considered 9 total strain scenarios for tradeoffs in biomass composition vs nutrient demands
  - Early-growth/high-protein biomass added up to $80/ton to MBSP to sustain high N/P levels in biomass (*does not include N/P recycle considerations from downstream)



- Alternative dewatering scenarios
  1) Replace membranes with DAF
     - Added substantial cost due to flocculant
  2) Replace membranes with EC
     - Appears competitive with membranes, but requires large-scale demonstration
  3) Replace membranes/centrifuge with filter press
     - Potential to reduce MBSP by ~$15/ton but requires large-scale demonstration and may require a flocculant (would add to cost)



Technical Accomplishments/Progress/Results: *Lipid Upgrading*



- Q3 milestone 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

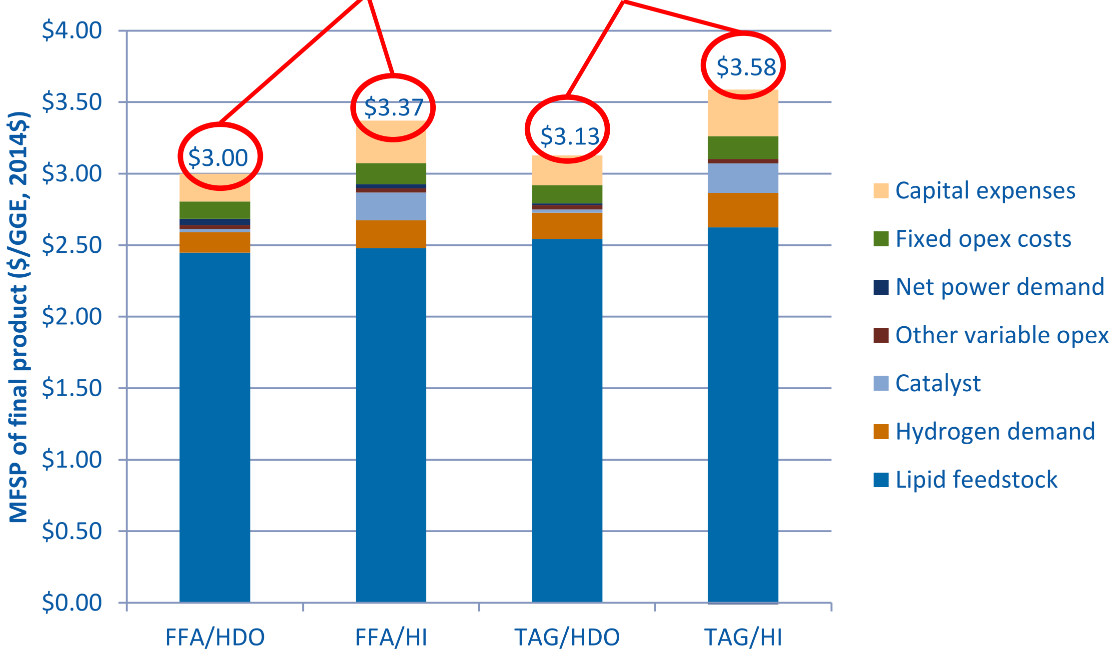
Blending Model Inputs				
	DO animal fat		DO+HI animal fat	
	Sample I		Sample E	
Diesel Properties	Value	Units	Value	Units
90% Vol. Dist. T	559.6	F	556.0	F
EP Vol. Dist. T	580.4	F	575.4	F
Aromatics	0.10	Vol %	0.30	Vol %
Sulfur	0.30	Wt ppm	0.40	Wt ppm
Specific Gravity	0.795	g/ml	0.777	g/ml
Flash Point	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)

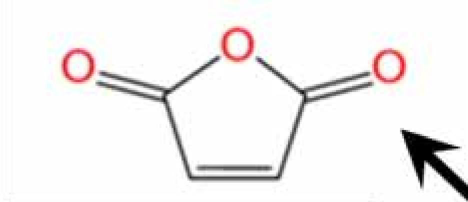
Δ value (blending model) = $0.22/gal

Δ cost (TEA) = $0.37 – $0.45/GGE



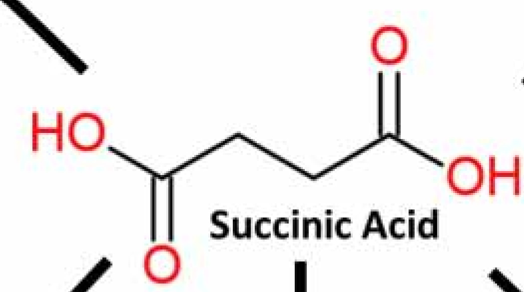
- Preliminary TEA based on experimental work for algae lipids (high-FFA), extrapolated to TAG lipids as additional case
- Current R&D is un-optimized for HI step (low LHSV, costly catalyst)
- TEA based on current R&D indicates not worth adding HI – adds more cost on TEA than expected value as a finished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

Succinic Acid

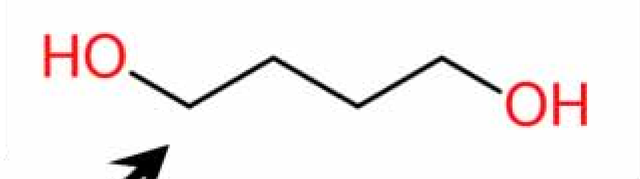


Maleic Anhydride

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

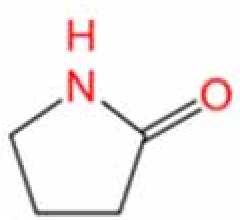


Succinic Acid



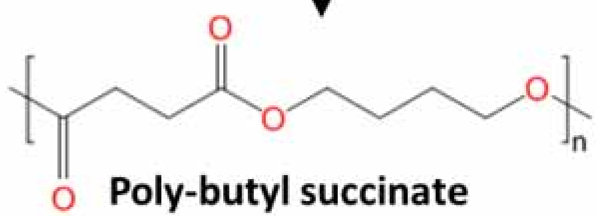
1,4 Butanediol

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



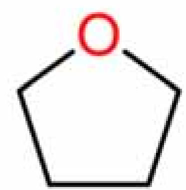
Pyrrolidinones

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