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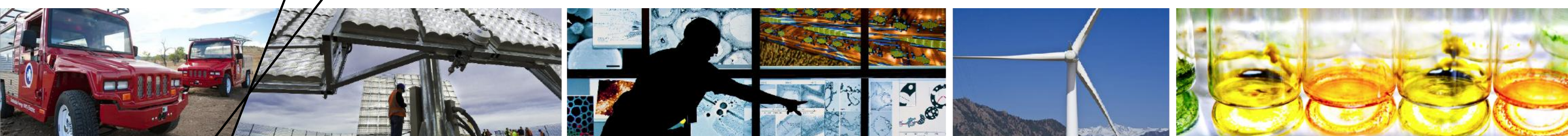
DOE Bioenergy Technologies Office (BETO) 2015 Project Peer Review

Algal Biofuels Techno-Economic Analysis



Algae Platform Review
March 24, 2015
Alexandria, VA

Ryan Davis
National Renewable Energy Laboratory

This presentation does not contain any proprietary, confidential, or otherwise restricted information

Goal Statement

Algae TEA Project Objective:

- Provide **process design and economic analysis support** for the algae platform, to **guide R&D priorities** for both NREL and BETO
  - Translate demonstrated or proposed research advances into economics quantified as $/ton feedstock or $/gal fuel price

- 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** towards goals through State of Technology (SOT) updates
  - Conduct **sensitivity analysis** to identify impact of key variables, design alternatives on overall economics
  - **Disseminate** rigorous, objective modeling and analysis information in a transparent way (the "design report" process)

- This project provides **direction, focus, and support for the BETO Program** by assisting in the development of cost benchmarks and future targets for use in MYPP planning
  - *Guide R&D towards economic viability, eventual adoption of algal biofuels/products into U.S. market*

Quad Chart Overview

Timeline

- Started: 2010
- Finish: 2017
- 75% complete

Barriers

- Barriers addressed
  - AFt-A: Biomass Availability and Cost
  - AFt-B: Sustainable Algae Production
  - AFt-H: Overall Integration and Scale-Up

Budget

	Total Costs FY 10 –FY 12	FY 13 Costs	FY 14 Costs	Total Planned Funding (FY 15-Project End Date
DOE Funded	$369k	$255k	$208k	$1,013k
Project Cost Share (Comp.)*	NA	NA	NA	NA

Partners

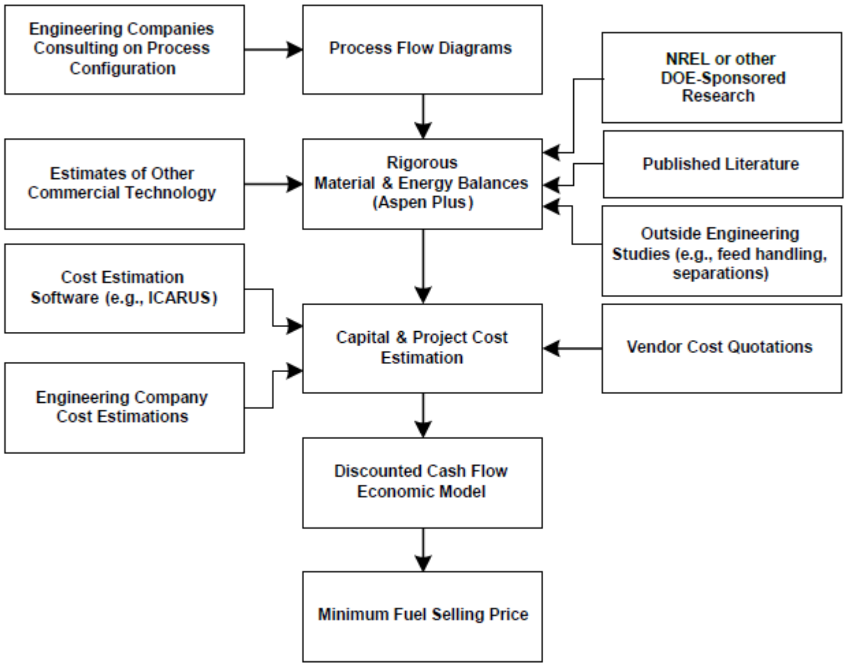
- Partners
  - No partners with shared funding
- Other interactions/collaborations
  - ANL – GREET LCA modeling team
  - PNNL – BAT RA modeling team, algal HTL modeling team
  - Consortia – substantial interaction with NAABB, SABC, ATP3
  - Industrial partners
  - Engineering subcontractors

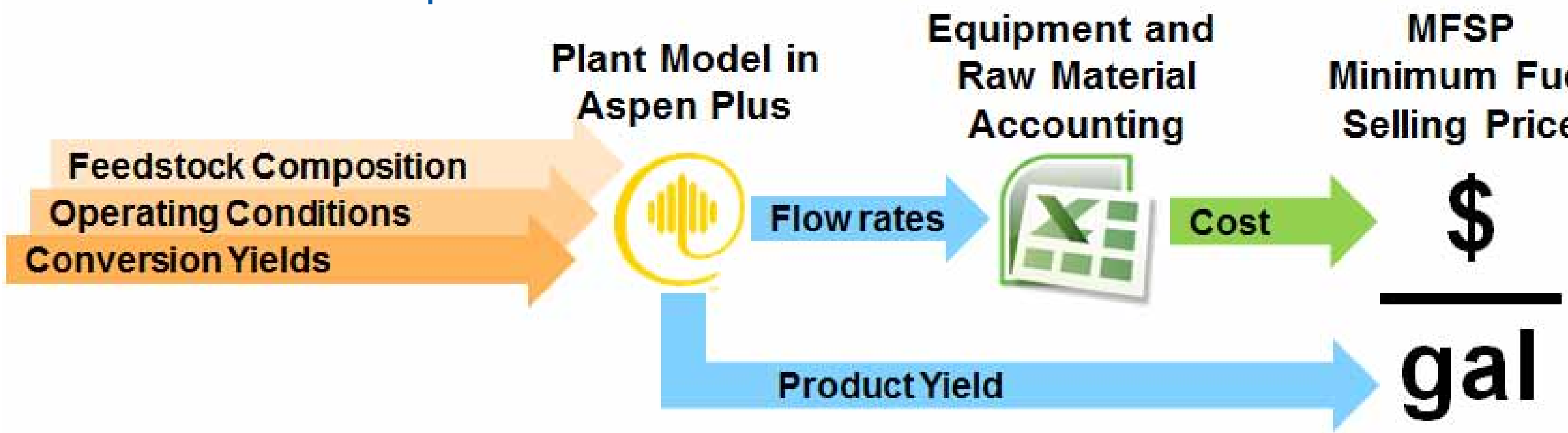
Project Overview

- This project has a 5-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 lipid extraction process in 2012 with ANL, PNNL
  - Expanded on harmonization to consider HTL pathway in 2013
  - Design report on novel fractionation process published 2014
- 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 model in Aspen Plus based on NREL/partner research data (where available), published literature (when necessary)
- Assumes *n*th-plant project cost factors and financing (ignores first-of-a-kind risks)
- 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
- Research advances → Higher modeled conversion → Lower production cost





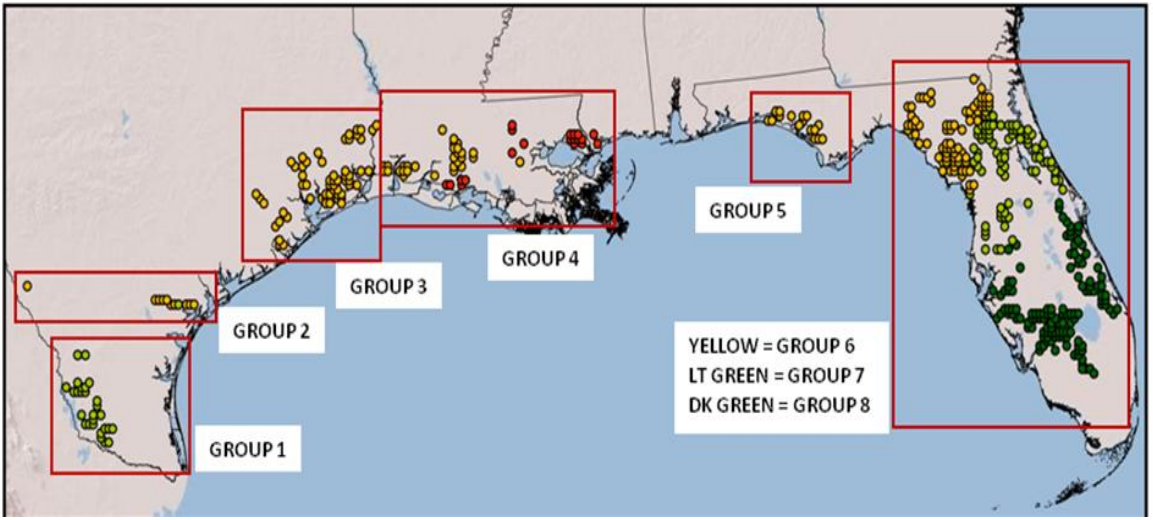
Approach (Management)

- Project management tracked using milestones
- Activities are highly integrated with research efforts, assist in prioritizations for R&D
  - Example – TEA identified more optimum process integration via whole-slurry processing (“CAP”)
- *Critical success factors:*
  - Leverage process design to 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:*
  - Lack of meaningful data (large-scale, year-round, commercially relevant conditions) for key aspects of process = increased modeling uncertainty
  - TEA shows that all algal biofuel pathways are highly dependent on cost of biomass production – critical to reach consensus on established system costs, consider new/novel designs

Project Milestones/Activities	FY14				FY15				FY16 (not yet set)			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Upstream process focus (biomass production logistics)												
Alternative farming strategy assessment		▶										
Summarize available cultivation pond cost estimates					▶							
Algal biomass production design report							▲	▶ ▲				
SOT assessment/out-year targeting updates								▲				
Downstream process focus (biomass conversion to fuels)												
Alternative co-product evaluations	▲									▼		
Process support for ANL LCA study on ALU process		▶										
Algal Lipid Upgrading (ALU) design report			▶	▲								
SOT assessment/out-year targeting updates						▶		▲				

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

Technical Accomplishments/Progress/Results: *2013 Algal HTL Harmonization*



http://www.nrel.gov/docs/fy12osti/55431.pdf

2012 Harmonization:

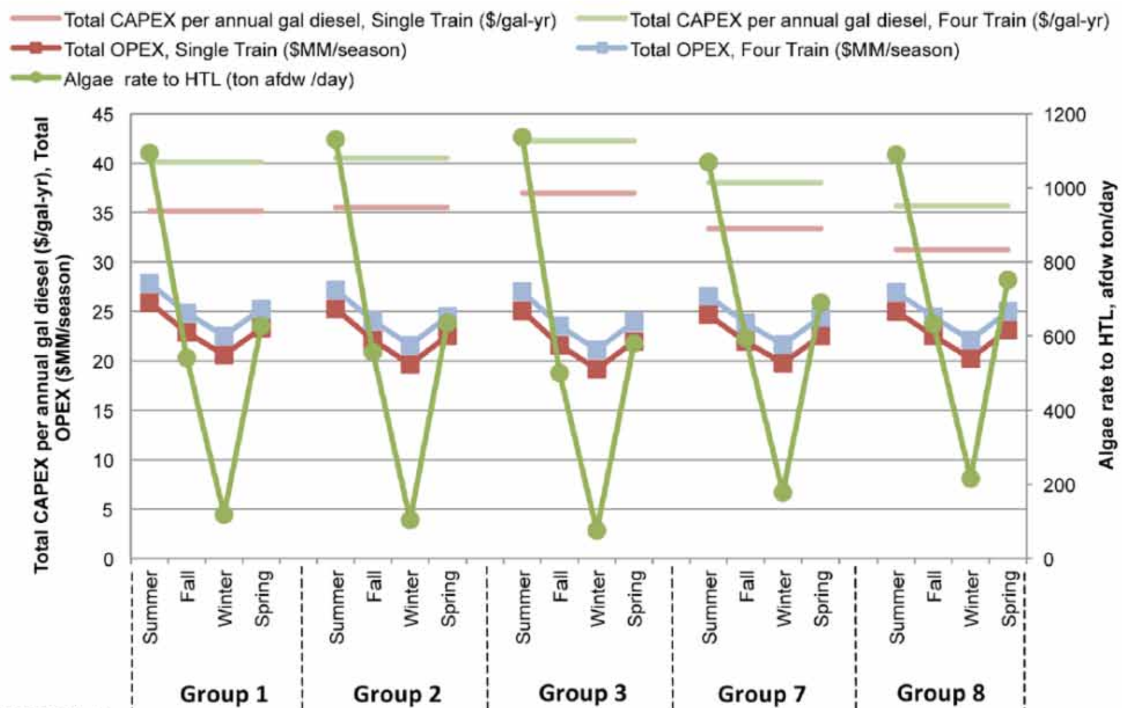
- Focused on lipid-only extraction to fuel
- PNNL RA modeling identified ~450 farms (4,850 ha each) required to collectively produce 5 BGY of lipid-derived RD
- Ranked according to favorability for high productivity + low water footprint
  - Groups 4-6 lowest ranking performance

2013 Harmonization:

- Focused on HTL conversion of whole biomass to fuel
- Refined RA model identified fewer sites required to meet same 5 BGY fuel target, driven by higher gal/ton fuel yield
  - Groups 4-6 dropped out of required site consortia

Davis *et al.*, ES&T 2014, 48, 6035-6042

2013 HTL Harmonization TEA Results



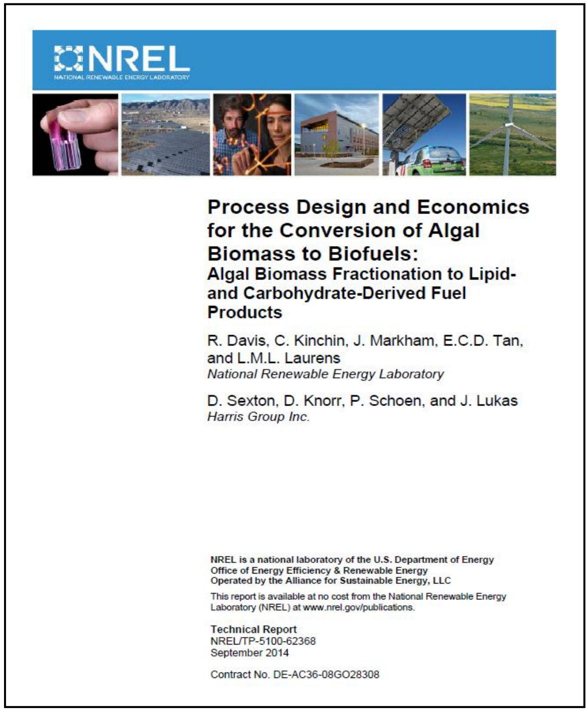
MDSP ($/gal)	Group 1	Group 2	Group 3	Group 7	Group 8
Four Train	$13.7	$13.4	$14.1	$12.6	$12.1
Single Train	$12.2	$11.9	$12.5	$11.2	$10.7
Annualized			$9.8		

Key TEA results:

- Consistent with 2012 harmonization, seasonal variability must be accounted for in algal biofuel models (neglecting variability under-estimates MFSP by ~$1-4/gal)
- Reduced variability leads to lower MFSP
  - Site Group 8 = lower max productivity, but also lower variation between summer and winter productivity → lowest MFSP of all groups
  - Driven by more efficient CAPEX utilization = lower CAPEX cost per annual gal

Technical Accomplishments/Progress/Results: *2014 ALU Design Report*

- Detailed report documenting TEA model projections in Aspen Plus; published September 2014
  - Transparent communication of design details and targets to show a plausible path to future cost goals
  - Identify primary cost drivers, evaluate alternative scenarios, understand cost sensitivities
- TEA model focused on a path to ~$4/GGE fuel costs via improved ALU ("algal lipid upgrading") conversion process
- Focus of design report scope is on *conversion technology* potential, excludes front-end aspects for biomass production
- Vendor quotes provided for all key operations via engineering contractor
- Thoroughly vetted through 12 industry peer reviewers
- Process pathway follows biochemical processing approach; selective conversion of specific constituents to products
  - Baseline configuration targets fuels from carb + lipid fractions



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Process Design and Economics for the Conversion of Algal Biomass to Biofuels:
Algal Biomass Fractionation to Lipid- and Carbohydrate-Derived Fuel Products

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Office of Energy Efficiency & Renewable Energy
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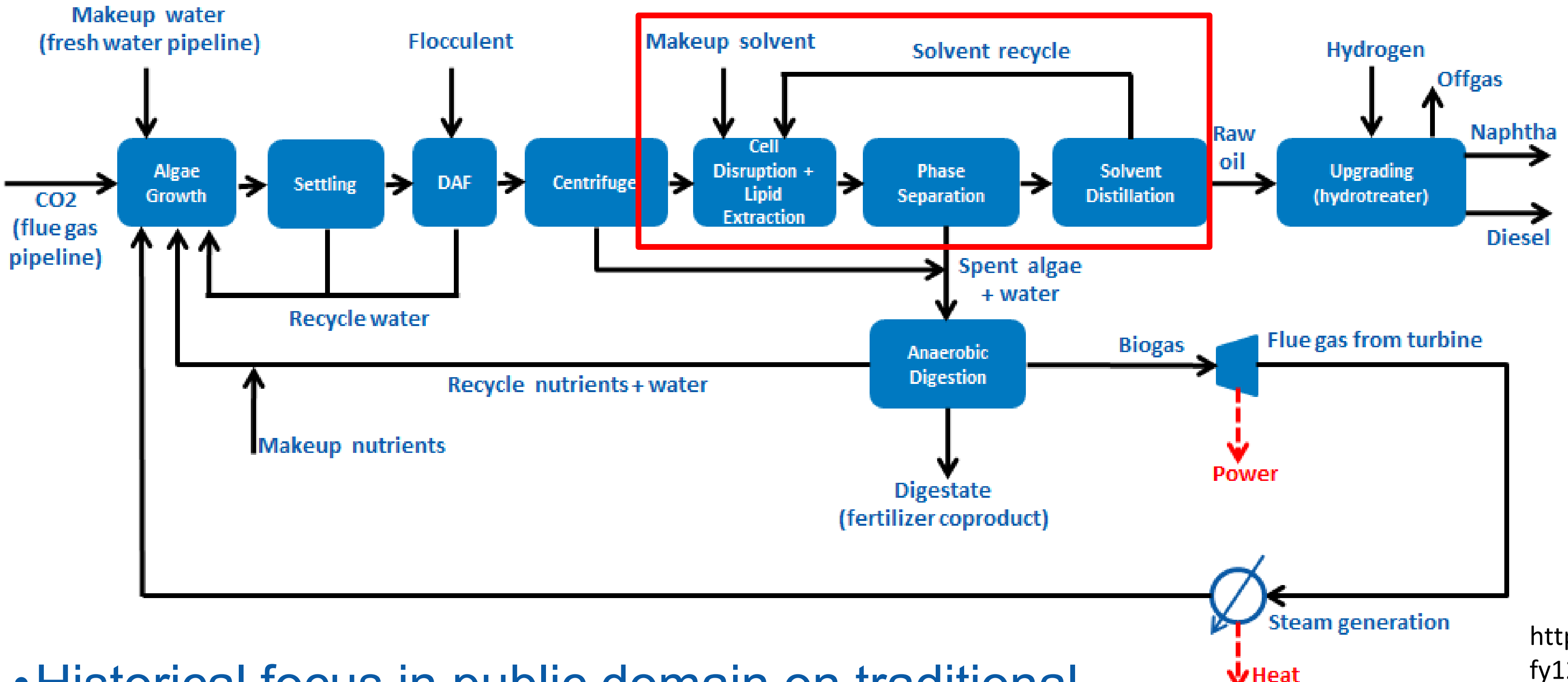
Technical Report
NREL/TP-5100-62368
September 2014

Contract No. DE-AC36-08GO28308

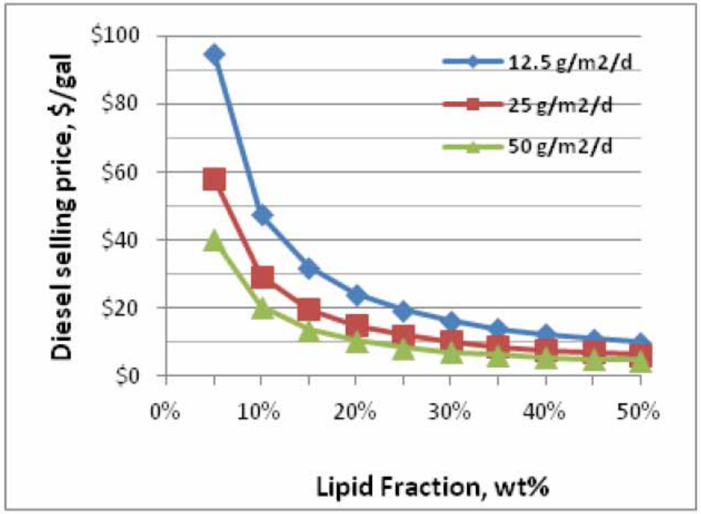
http://www.nrel.gov/docs/fy14osti/62368.pdf

Background: Prior TEA Focus – Lipid-Only Extraction (Benchmark as of 2013 Peer Review)

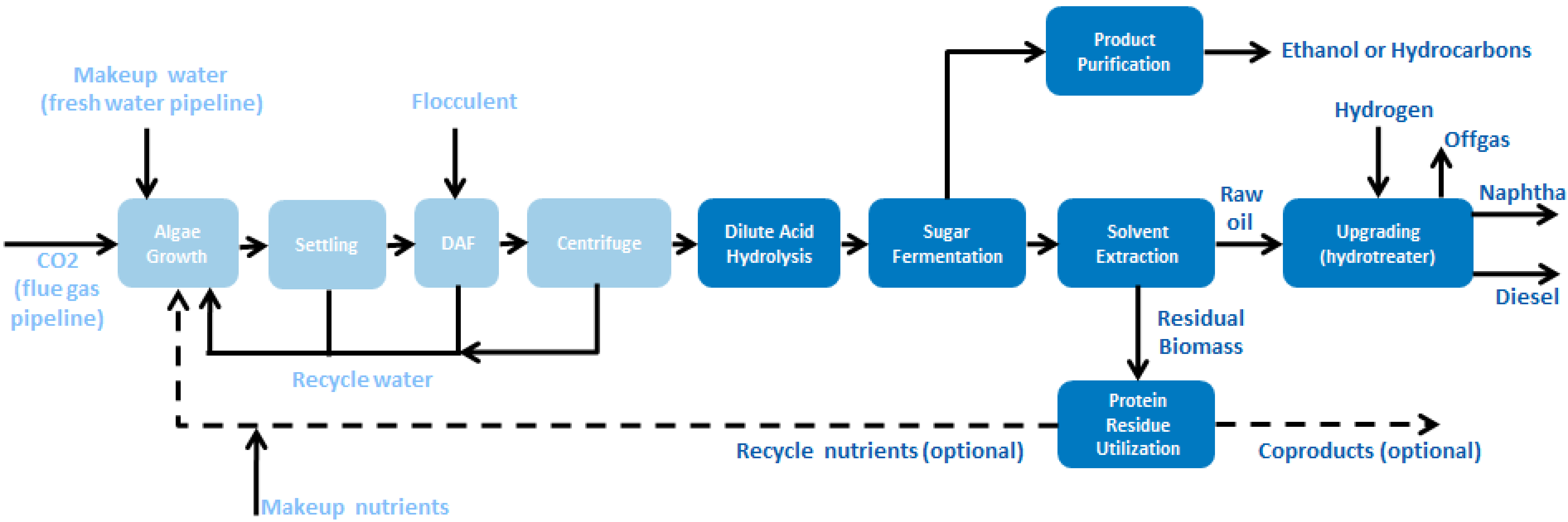


http://www.nrel.gov/docs/fy12osti/55431.pdf

- Historical focus in public domain on traditional lipid extraction pathways; challenged by:
  a) No definition of "traditional": majority of TEA assumed a black-box lipid extraction process, but data largely lacking on high yield/wet extraction methods → increased uncertainty
  b) Asymptotic limits to cost reductions, dictated by achievable yields (≤50% lipids = ≥50% unutilized biomass)



New Approach: Biochemical Processing to Multiple Products/ Co-Products ("ALU Fractionation")

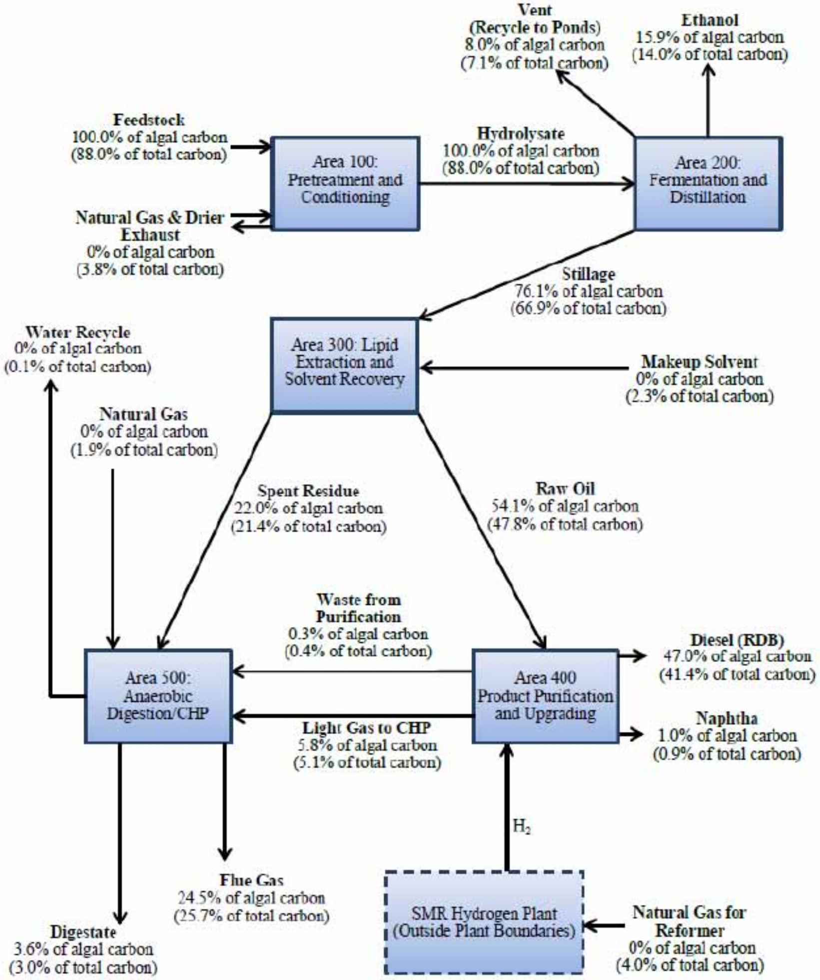


- Alternative approach: biochemical processing for selective conversion of multiple biomass components to multiple fuel products/coproducts
    - Potential for similar fuel yields as HTL, but non-destructive conversion of biomass allows high selectivity towards numerous product options
    - "Plug and play" flexibility for conversion of carbohydrate, lipid, and protein fractions
    - Experimentally demonstrated high lipid extraction yield on wet biomass

2014 Design Report Results: Costs, Yields, Carbon Balances

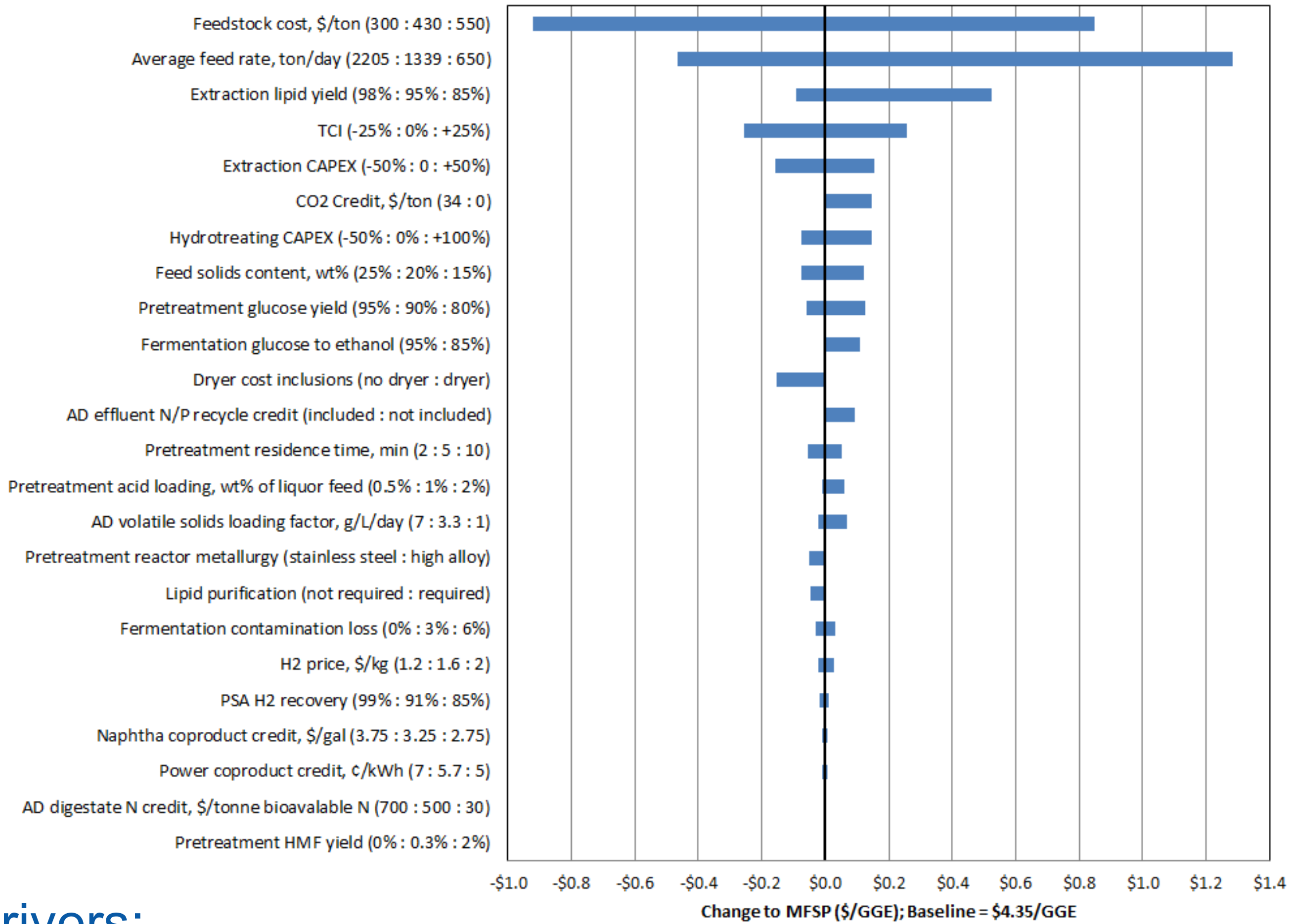
Metric	Target
Minimum Fuel Selling Price ($/GGE, 2011$)	**$4.35**
Feedstock Contribution ($/GGE, 2011$)	$3.05
Conversion Contribution ($/GGE, 2011$)	$1.30
Yield (GGE/ton afdw)	141
RDB Yield (GGE/ton afdw)	105
Ethanol Yield (GGE/ton afdw)	36
C Efficiency to Fuels from Biomass	64%
Feedstock	
Feedstock Cost ($/ton afdw)	$430
Pretreatment + Conditioning*	
Solids Loading (wt%)	20% *[15-25%]*
Acid Loading (wt% versus feed water rate)	1% *[2%]*
Fermentable Sugar Release ("glucose yield")	90% *[74%]*
Glucan to Degradation Products	0.3% *[1.5%]*
Hydrolysate solid-liquid separation	No *[No]*
Sugar Loss	*NA (CAP process)*
Fermentation*	
Total Feed Solids Loading (wt%)	20% *[~6% sugars]*
Fermentation Batch Time (hr)	36 *[18]*
Sugar diversion to organism seed growth	4% *[ND]*
Fermentable Sugar to Product	95% *[84%]*
Lipid Extraction + Upgrading*	
Solvent Loading (solvent/dry biomass ratio, wt basis)	5.0 *[5.9]*
Total convertible Lipid Extraction Yield	95% *[87%]*
Polar Lipid Impurity Partition to Extract	33% *[<11.5%]*
Hydrotreating RDB Yield (wt% of oil feed)	80% *[ND]*
Hydrotreating H_2 Consumption (wt% of oil feed)	1.7% *[ND]*

Process Carbon Balances



**Current experimental values shown in brackets*

Framing the Analysis: Sensitivity Scenarios



- Primary drivers:
  - Feedstock cost: reducing to $300/ton = $3.42/GGE (includes cultivation CAPEX)
  - Design feed rate: lose economy of scale at lower design capacities
  - Extraction yield: critical to achieve high lipid recovery given up-front costs
  - Total Capital Investment (uncertainty inherent to TEA methodology)

Collaboration with ANL: LCA Examination for ALU/HTL Pathways

Argonne NATIONAL LABORATORY

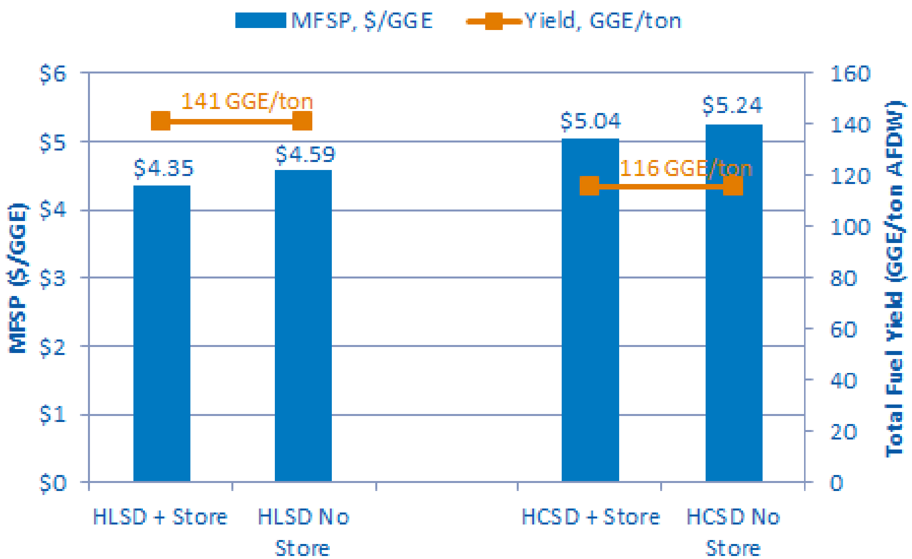
Credit for slide content: Ed Frank, ANL

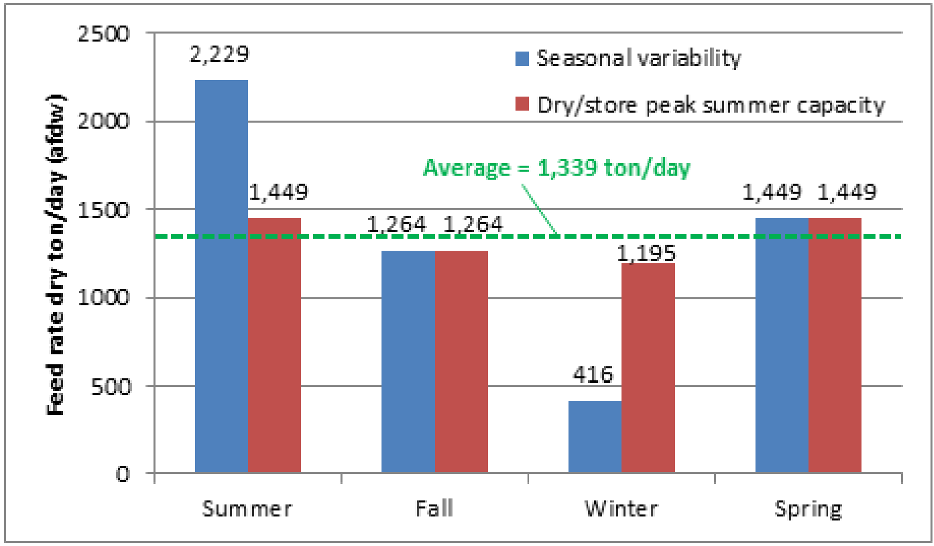
Scenario	Year	MFSP ($2011/GGE)	Seasons	Productivity (g/m²/d)	WTW GHG (gCO2$_2$e / MMBTU)		
					Fuel cycle	Infrastructure	Total
Baseline ALU	FY12	$ 20.79	3	15.5	67500	8300	75800
National Scale HTL	FY13	$ 11.34	4	14.6	40100	-	-
HTL design case	FY14	$ 4.49	4	30	35700	1700	37400
ALU design case	FY14	$ 4.35	4	30	34900	2100	37000

MFSP - Minimum fuel selling price
GGE - Gallons of gasoline equivalent
WTW GHG - Well to wheels (whole lifecycle) greenhouse gas emissions

The TEA / LCA / RA collaboration guides BETO's system integration and design

TEA for Biomass/Processing Alternatives





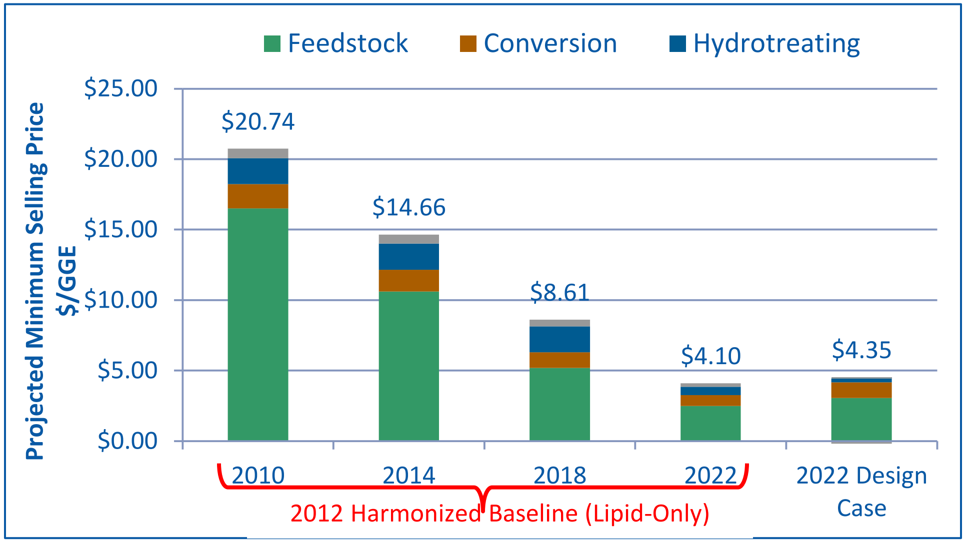
- Switch to no drying/storage of excess summer capacity (feed material straight from upstream cultivation) = 4-6% MFSP increase
  - Suggests that this option is also feasible for economics if full LCA identifies NG for summer drying is problematic
  - Must also consider equipment operability/design issues for such large seasonal swings in throughput
- Switch from HLSD to HCSD = 14-16% MFSP increase
  - Driven by 18% reduction in total GGE/ton yield (ethanol/RDB ratio increases from 35% to 50%, lower energy content in ethanol)
  - Moving forward, will be critical to consider what is ultimately viable for front-end cultivation targets given tradeoff between productivity and composition (lipid content)
    - HCSD biomass = earlier harvest point = higher g/m^2/day productivity vs HLSD
    - **Reasonable target case may be between these points** = $4.35-$5.04/GGE, 116-141 GGE/ton

Relevance

NREL TEA modeling is highly relevant to BETO goals:

- Helps guide R&D, DOE decisions, out-year target projections
  - *Technical targets (yields, process performance, etc)*
  - *Cost targets (forms basis for BETO MYPP goals)*
- Identifies key R&D directions (yields, coproduct opportunities, etc)
- Analysis can serve a wide variety of stakeholders
  - *Industry (facilitate interaction between industry, NREL, DOE)*
  - *Research community, decision makers*

Cost Projections From November 2014 MYPP:



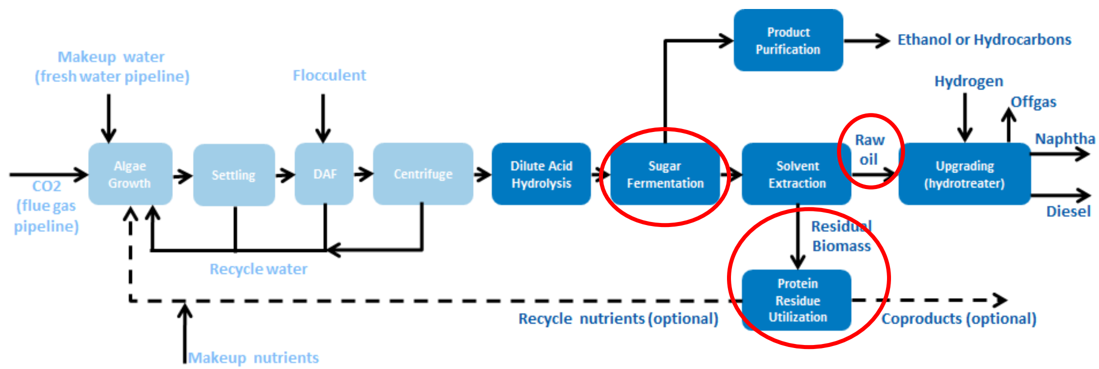
- This project supports BETO's efforts to encourage collaboration across multiple organizations:
  - Continued interactions with harmonization partners (ANL – LCA, PNNL – BAT, TEA teams)
  - Interactions with consortia:
    - NAABB: considered TEA implications for strains, dewatering technologies developed under NAABB
    - SABC: formed the basis for the ALU design case pathway
    - ATP3: TEA modeling support for test-bed sites across U.S., leveraging data to inform SOT and future target cultivation metrics/costs

Nov 2014 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

- Algal biomass design case:
  - Develop a design report for the front-end process (cultivation through dewatering); effort will refine prior modeling estimates with more rigor, to understand what it "really takes" to get to algal biomass cost targets <$500/ton – *Q3-4 milestones (2), Q4 Quarterly Progress Measure*
  - Key focus of work will be to investigate potential alternative low-cost cultivation options in addition to traditional raceways, and identify key cost drivers behind cultivation systems
- 2015 State of Technology assessments for FY15 R&D data:
  - Conduct preliminary SOT estimate to quantify fuel costs based on experimental data for ALU conversion ("CAP") process – *Q2 Quarterly Progress Measure*
  - Finalized SOT assessment for fully integrated process; including measured productivity data for biomass cost model (from ATP3), and updated R&D data for conversion (NREL) – *Q4 milestone*
- TEA support for ATP3 consortia to run full year cultivation data from all test-bed sites through biomass production model – *Q4 milestone (ATP3)*

- FY16 and beyond: TEA support for algae platform in exploring options for further cost reductions ($3/GGE):
  - Go/no go milestone to assess viability for alternative higher-value coproduct options (vs AD) within context of ALU fractionation model – *Q2 FY16 go/no go*
  - Likely to require value-added coproducts to achieve $3/GGE targets, given high biomass cost



Higher-value coproduct examples:
- *Carbs: organic acids*
- *Lipids: PUFAs, epoxies*
- *Protein: fishmeal, bioplastics*

Summary

- NREL Algae TEA project has made important achievements since 2013 peer review
  - Expanded on prior harmonization efforts to consider HTL conversion
  - Improved upon original 2012 ALU pathway model with establishment of fractionation process – promising yields, reduced uncertainty, improved costs
  - Established out-year design case target model presenting a path to $4.35/GGE; leveraged by BETO to set MYPP projections
  - Quantification of sustainability metrics for design case conversion model
- TEA work is highly relevant to supporting program directions for BETO, near- and long-term R&D for NREL and partners
- Supports industry and research community via design reports, communication with stakeholders, external collaborations
- Further efforts planned moving forward around biomass cultivation/logistics modeling, consideration of low-cost farming options, assessment for coproduct opportunities

NREL, Sept, 2010, Pic #18229

Additional Slides

Responses to Previous Reviewers' Comments from 2013

- There is some concern as to how current the data used in the model are because of the stated lack of availability of primary sources.
- Regarding the need for realistic/current operational data, this is a point we recognize and continue to place a high priority on. As the reviewers note, this is typically challenging as much of the data on real-world, large-scale operations are held privately by industry with an understandable reluctance for such data to be utilized in publicly documented models. However, improvements continue to be made here as data on the most critical operation (cultivation) is currently being generated by the ATP3 consortium of which NREL is a member, with upcoming milestones to run a full year of productivity data through NREL's biomass cost models for all participating test-bed sites across the U.S. Additionally, with the change to the new ALU fractionation model, all pertinent data related to back-end conversion steps are now based on first-hand experimental work conducted at NREL.

- Model needs to be compared with a design for less-than-peak capacity.
- While the prior 2012 harmonization models were based exclusively on designing equipment for peak (summertime) capacity, newer models as documented in NREL's 2014 ALU design report consider two options: (1) size all equipment for peak capacity, or (2) divert excess capacity to be dried and stored for use in the winter (thus designing equipment to a capacity lower than peak/summertime). More optimum economics were identified for option (2), thus the ALU design case model is in fact designed for less-than-peak capacity, acknowledging logistical questions that may follow this scenario.

- TEA needs to be extended to consider a protein meal co-product option.
- While we had briefly considered animal feed as a coproduct option in our prior 2012 harmonization modeling (e.g. http://www.nrel.gov/docs/fy12osti/55431.pdf, section 4.1), we revisited this option in more detail during preliminary feasibility modeling efforts in early FY14 to identify an optimum use for the protein residue in NREL's ALU design report. The results of the assessment could not be shared in the presentation due to time constraints, but are provided as shown in slide 23. In summary, at an assumed protein meal value of $350/tonne (higher than typical feed prices), economics fared worse than the base case routing the residue to anaerobic digestion, and penalties were also incurred for sustainability given the loss of nutrient recycle and the need to dry the protein feed using natural gas.

Publications, Patents, Presentations, Awards, and Commercialization

Publications (since 2013 review):

- R. Davis, C. Kinchin, J. Markham, et al., "Process design and economics for the conversion of algal biomass to biofuels: Algal biomass fractionation to lipid- and carbohydrate-derived fuel products." NREL Technical Report NREL/TP-5100-62368, September 2014. http://www.nrel.gov/docs/fy14osti/62368.pdf
- L. M.L. Laurens, N. Nagle, R. Davis, et al., "Acid-catalyzed algal biomass pretreatment for integrated lipid and carbohydrate-based biofuels production." *Green Chemistry* (2015) 17: 1145-1158
- J.C. Quinn, R. Davis, "The potentials and challenges of algae based biofuels: A review of the techno-economic, life cycle, and resource assessment modeling." *Bioresource Technology* (2014), http://dx.doi.org/10.1016/j.biortech.2014.10.075
- R. Davis, D. Fishman, E. Frank, et al., "Integrated evaluation of cost, emissions, and resource potential for algal biofuels at the national scale." *Environmental Science & Technology* (2014) 48: 6035-6042
- C.E. Canter, R. Davis, M. Urgun-Demirtas, E.D. Frank, "Infrastructure associated emissions for renewable diesel production from microalgae." *Algal Research* (2014) 5: 195-203.
- A. Miara, P.T. Pienkos, M. Bazilian, et al., "Planning for algal systems: An energy-water-food nexus perspective." *Industrial Biotechnology* (2014) 10: 202-211.
- M. Bazilian, R. Davis, P.T. Pienkos, D. Arent, The energy-water-food nexus through the lens of algal systems." *Industrial Biotechnology* (2013) 9: 158-162.

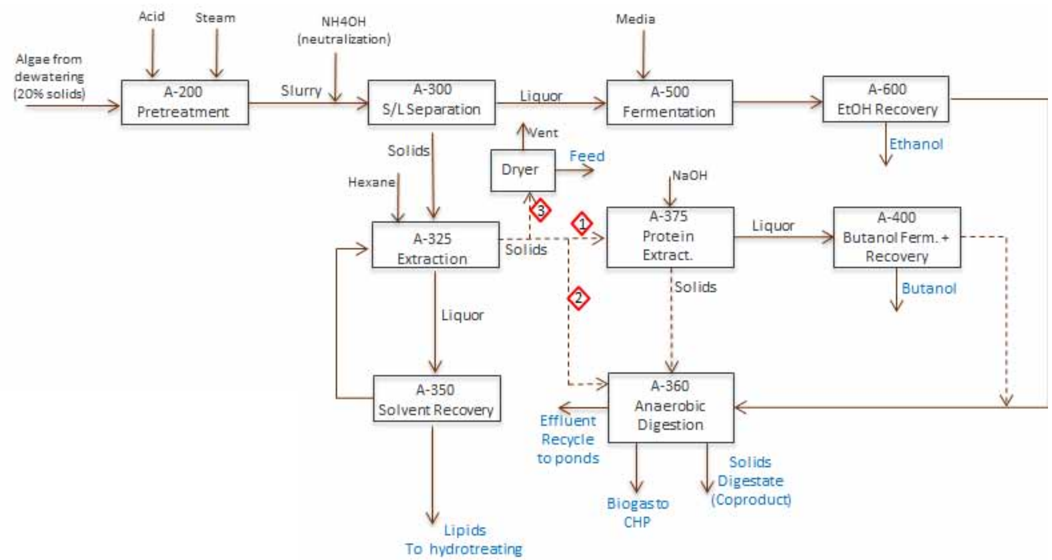
Presentations (since 2013 review):

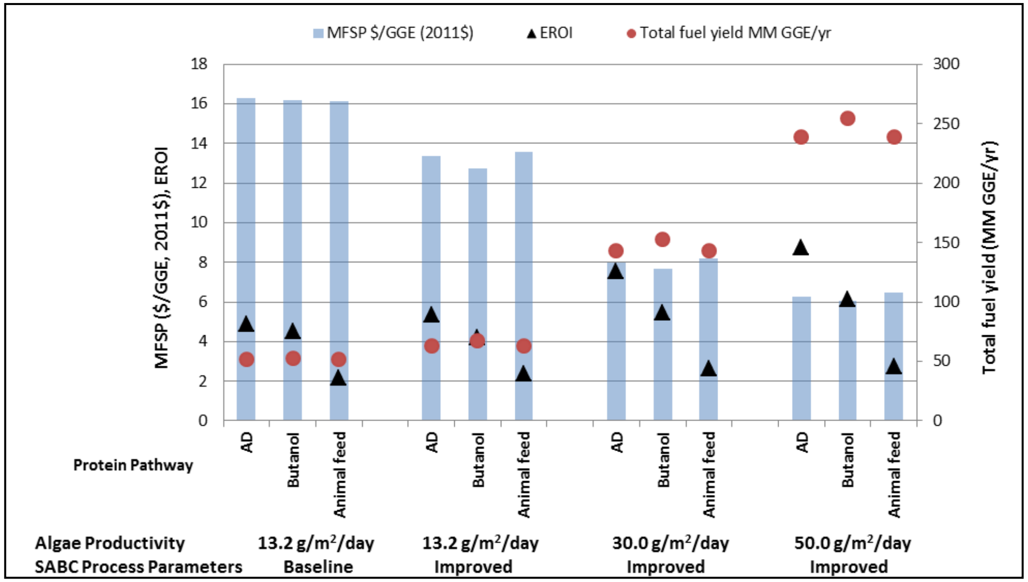
- R. Davis, C. Kinchin, J. Markham, et al., "Techno-economic analysis for a novel route to algal biofuels via biochemical processing: Process and cost targets towards achieving viability." Presented at the Algae Biomass Summit, San Diego, CA; October 2014.

Backup Slides

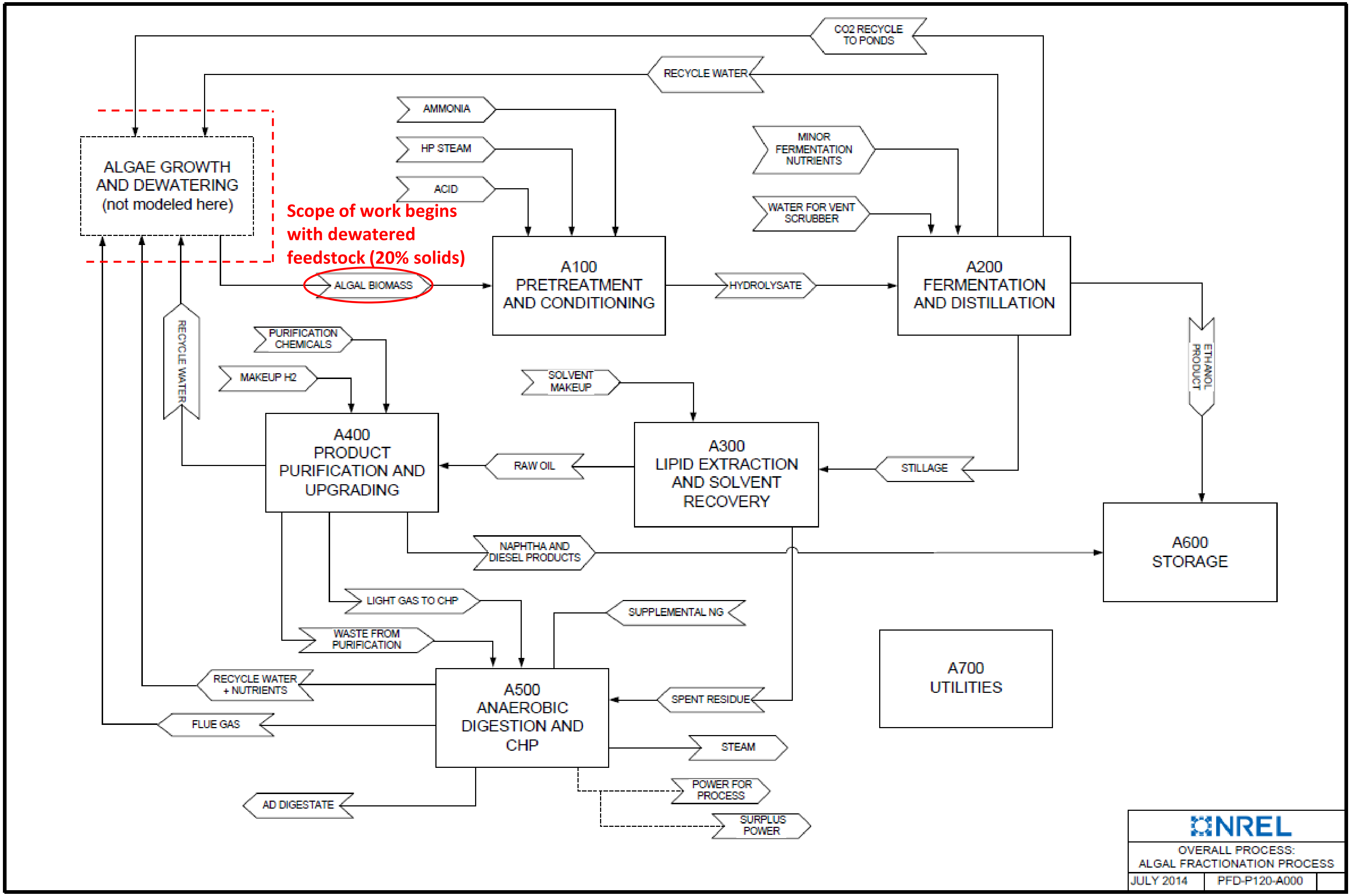
Protein Coproduct Tradeoff Assessment

- Early TEA work for fractionation process considered three options for protein residue utilization:
  - "Fermentation" to C4+ alcohols
  - AD
  - Dry and sell as animal feed @ $350/tonne
- Analysis found poor results for animal feed with higher MFSP and much lower EROI (loss of nutrient recycle, NG use for drying)
- Comparable MFSP between butanol vs AD options, but better EROI for AD given lower energy demands and higher biogas production
- Conclusions led to selection of AD for design report basis, but opportunity for more evaluation moving forward





Overall Process Schematic – 2014 ALU Design Report



Design & Financial Assumptions – ALU Design Report

Process Targets	
Feedstock rate	1,339 ton/day (AFDW, annual average)
Biomass composition	41% lipids (as FAME); 38% carbohydrates
On-line time	330 days/year
Fermentable sugar yield from PT	90%
PT acid concentration	1% vs liquor feed to PT
Fermentable sugar to ethanol	95%
Lipid extraction yield	95%
Polar lipid impurity partitioning to extract	33%
Extraction solvent loading	5 kg hexane/kg dry biomass
Hydrotreating yield, lipid-to-diesel	80 wt% of feed

Financial Assumptions	
Target internal rate of return (IRR)	10%
Cash flow methodology	Discounted cash flow rate-of-return (DCFROR)
Cost-year dollars	2011
Debt : equity ratio	60% debt / 40% equity
Loan terms	10 year, 8% interest
Tax rate	35%
Depreciation schedule	MACRS: 7 year (general), 20 year (power)
Plant lifetime	30 years
Feedstock cost	$430/ton (AFDW), 20% solids from dewatering
Power coproduct credit	5.7 ¢/KWh

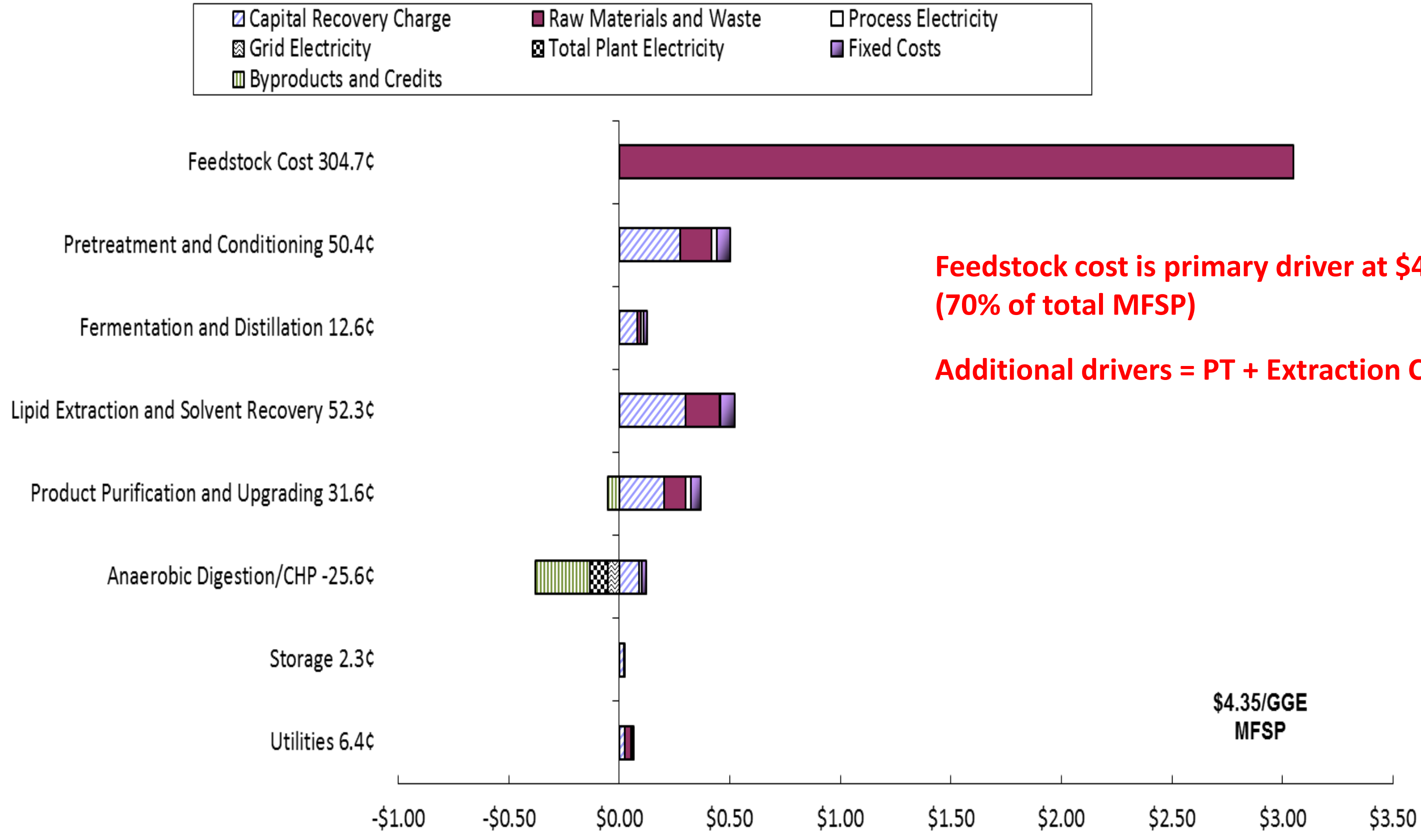
ALU Design Report: Conversion Stage Sustainability Metrics

Sustainability Metric	2022 Design Case (Summer Storage Base Case)	2022 Design Case (No Storage Alternative)
GHGs (g CO_2-e/MJ fuel) (fossil emissions)	32.2	10.4
Fossil Energy Consumption (MJ fossil energy/MJ fuel)	0.33	0.17
Total Fuel Yield (GGE/dry ton)	141	141
Biomass Carbon-to-Fuel Efficiency (C in fuel/C in biomass)	63%	63%
Total Carbon-to-Fuel Efficiency (C in fuel/C in biomass + NG)	55%	58%
Water Consumption (m^3/day; gal/GGE fuel)	2,563 m^3/day; 3.6 gal/GGE [1]	1,876 m^3/day; 2.6 gal/GGE [1]
Net Electricity Export (KWh/GGE)	0.9	0.9

[1] Process water demands only; does not include moisture content of incoming feedstock

- Sustainability metrics run for design case; only considers conversion stage (not a full WTW LCA)
- Including consideration of sustainability metrics provided quantified comparison for GHG, fossil, water benefits when switching to no storage of excess summer biomass (contrast vs TEA result)
- Full WTW analysis required to fully understand sustainability impacts, but useful to consider conversion stage alone as a quick assessment in design report

ALU Design Report: Cost Drivers



Feedstock cost is primary driver at $430/ton (70% of total MFSP)

Additional drivers = PT + Extraction CAPEX