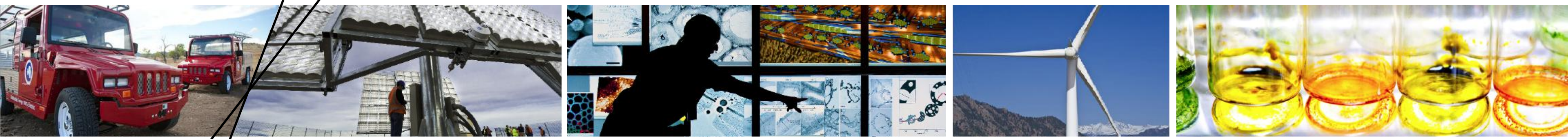
Algal Biofuel Techno-Economic Analysis



Algae Peer Review

May 22, 2013

Alexandria, VA

Ryan Davis
National Renewable Energy Laboratory

Goals and Objectives

NREL, Sept 15, 2010, Pic #18071

- The goal of this task is to **develop baseline techno-economic analysis** and user models for algal biofuels
  - *Serves as a benchmark against which process variations can be compared*

- This task directly supports the Biomass Program by assisting in the development of **baseline costs and future cost targets**
  - *Nov 2012 MYPP goal: "Assess multiple algae production and processing systems for **commercial viability** and sustainability"*
  - *Leverages decades of experience in cost-driven R&D for other biomass conversion platforms (biochemical, thermochemical, etc)*

- Using techno-economic analysis (TEA) and modeling, NREL provides **direction, focus, and support** to the biomass program and algae-related projects, guiding R&D towards program goals
  - *Algae technologies under development can be incorporated into the models in order to quantify their economic impact*
  - *Experimentally verified data will be used in the models to quantify progress towards program goals*
  - *Sensitivity analysis is used to quantify the impact of key variables on overall economics*

Quad Chart Overview

Timeline

- Start: June 2010
- End: Sept. 2017
- ~ 40% Complete

Barriers

- Ft-A. Feedstock Availability and Cost
- Ft-M. Overall Integration and Scale-Up
- Ft-N. Algal Feedstock Processing

Budget

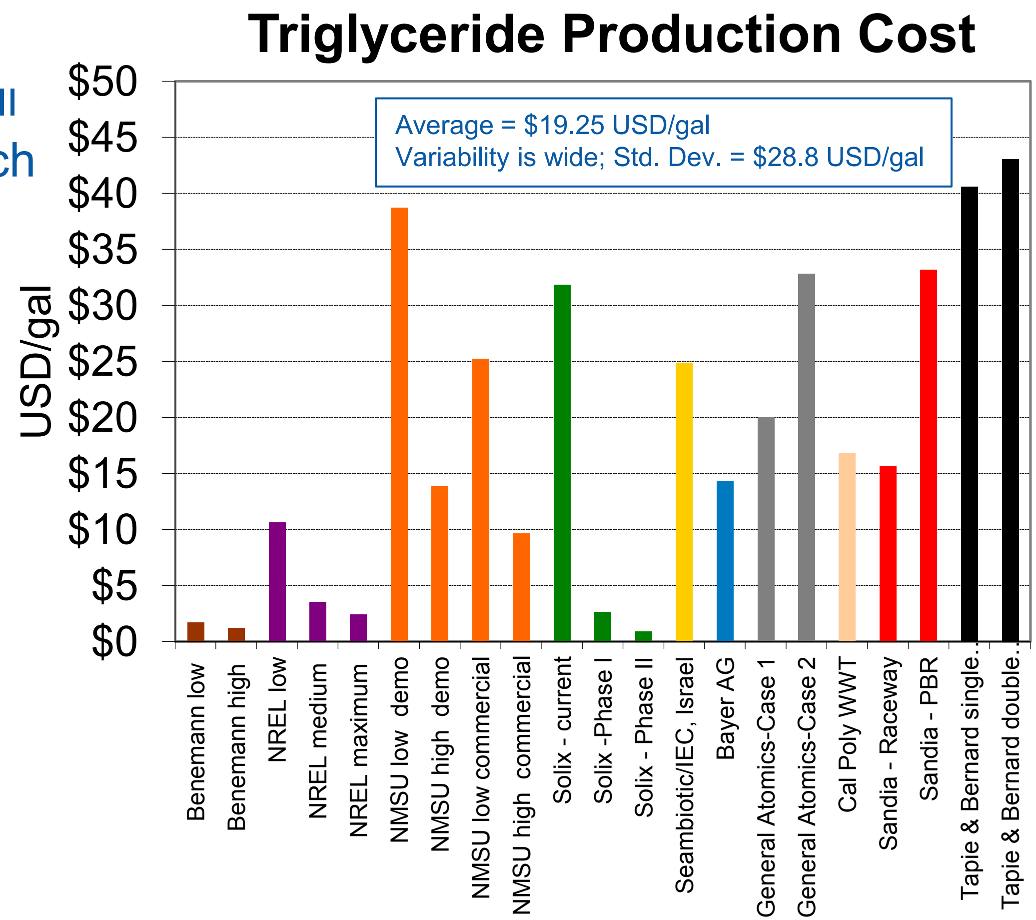
- Total funding (since project start): $644,000
- FY12: $210,000
- FY13: $200,000
- No ARRA Funding

Partners

- DOE BETO HQ and GO
- Algae Project PIs
- ANL, PNNL (National Laboratory partners for harmonization)
- Consortia groups: NAABB, SABC, ATP^3
- Harris Group (Subcontractor)

Project Overview

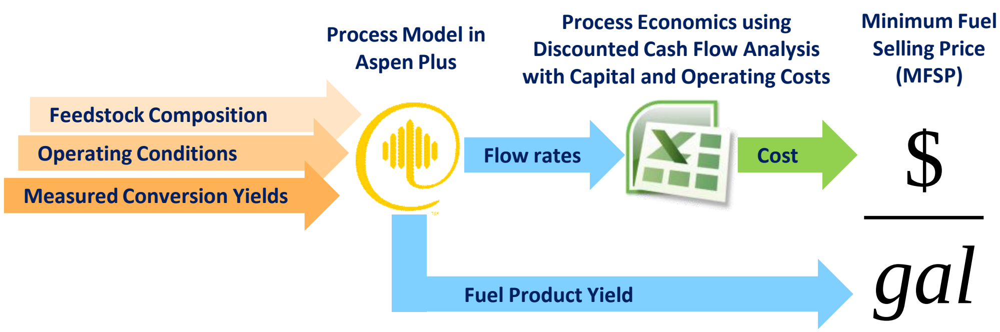
- Multiple algae economic studies have been conducted, with enormous variation
- The goal of this work is to develop rigorous algae cost models for near-term targets
  - Objective, transparent benchmarks and evaluation of alternative technologies
- This project leverages several prior NREL research activities
  - Aquatic species program (ASP)
  - DOE Biomass Algal Roadmap
  - Analysis conducted for EPA under RFS II
- Conceptual models made from scratch
- Phased approach:
  1) *Develop baseline models using best available data*
  2) *Peer review models*
  3) *Incorporate technologies under development*
  4) *Assist in cost target development*
- Scope of analysis:
  - Open pond, autotrophic cultivation
  - Scope includes upgrading algal oil to diesel blend stock (hydrotreating)
  - Prior efforts have also considered PBR, heterotrophic cultivation

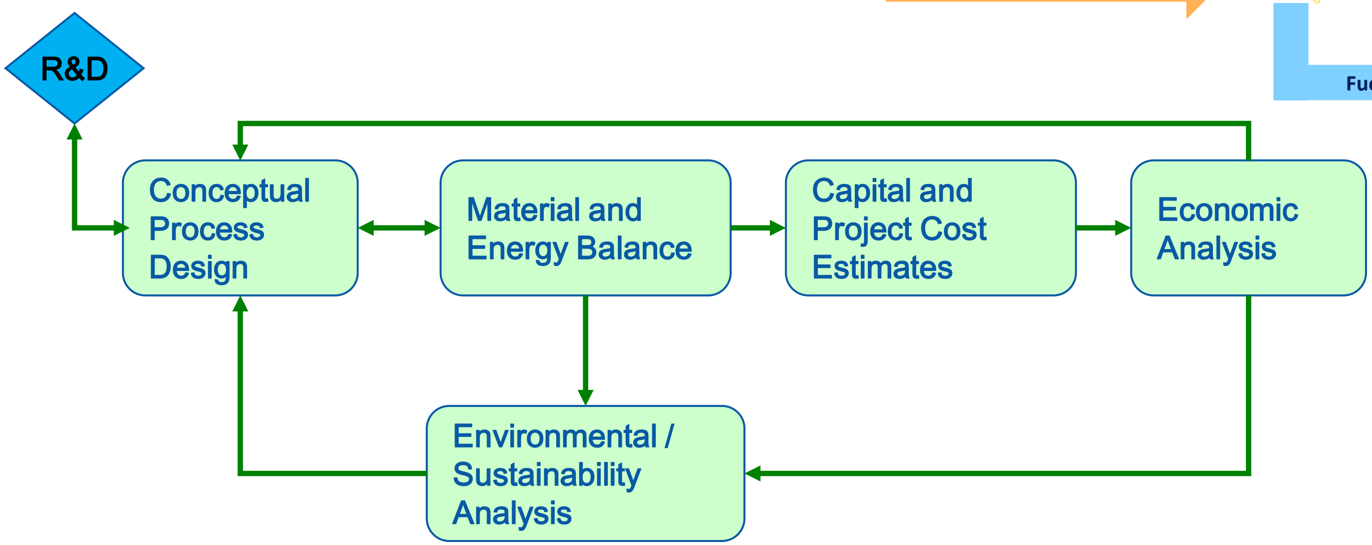


Sun *et al*, Energy 2011

Approach

- Rigorous process models developed in Aspen Plus for material and energy balances
- Capital and operating costs developed in Excel
- Cost data derived from vendors, cost databases, literature, etc.
- Financial assumptions consistent with other established/vetted platforms
- Cash flow analysis to find minimum product selling price at 10% internal rate of return (IRR)
- Iterate to refine models as new data becomes available
  - Identify primary cost drivers, evaluate alternative technologies, understand cost sensitivities
- Track progress using milestones
  - Milestone table provided in “backup slides”





Accomplishments

Notable accomplishments (FY11-12):

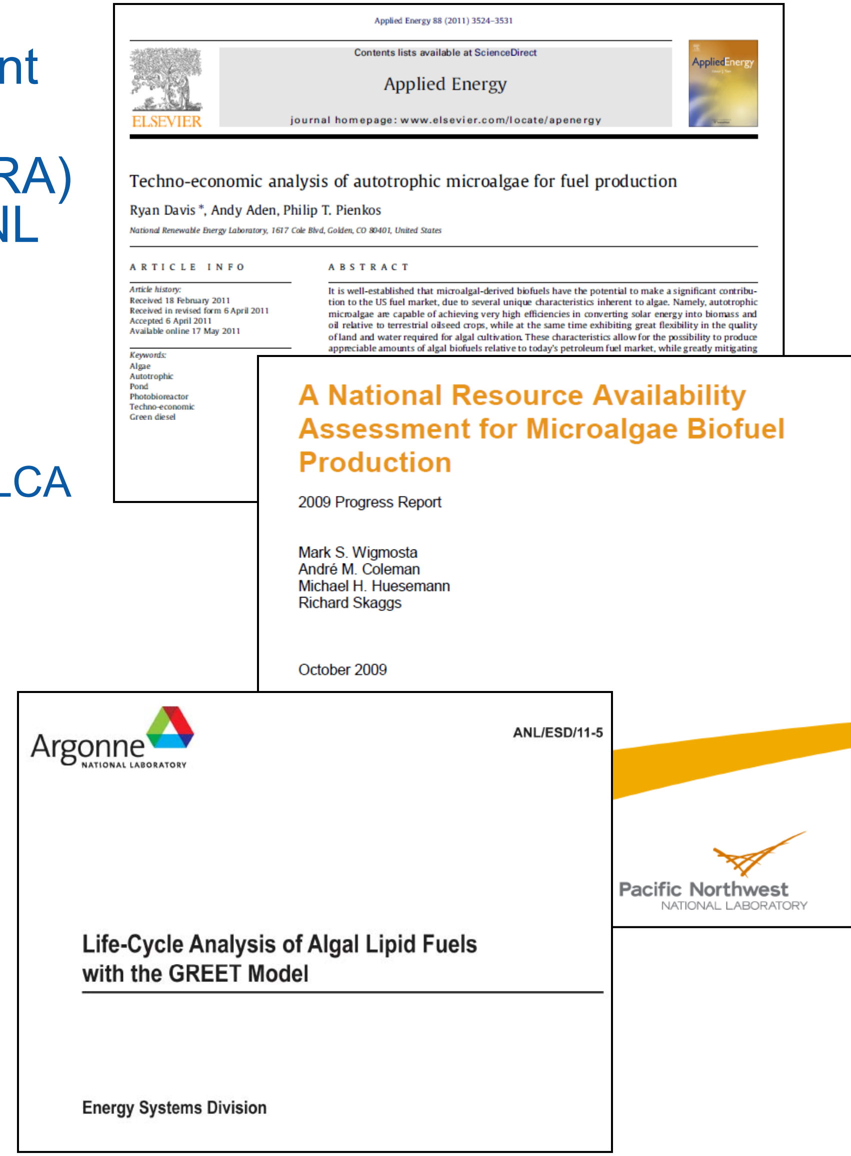
- Completed and published results of early TEA analysis for autotrophic pond vs PBR growth (*Applied Energy* 2011)
- Expanded TEA model for open pond pathway into comprehensive harmonization analysis with ANL, PNNL
  - Harmonization workshop with research, industry stakeholders
  - Rigorous re-working of models, published in joint report (June 2012)
- Exercise harmonization baseline to help establish current and future process + cost targets for DOE MYPP

Current status (FY13):

- Beginning new harmonization analysis for algal hydrothermal liquefaction (HTL), joint with ANL + PNNL
- Expanding algal lipid upgrading (ALU) pathway to evaluate alternative processing technologies, refine cost estimates using vendor quotations
- Evaluating early heterotrophic models for further analysis in NREL biochemical conversion platform (biological sugar conversion)
- Leveraging autotrophic models for use in ATP^3 consortium: validate models using demonstrated data at meaningful scale from multi-region test-bed facilities; serve as interface between ATP^3 performers and broader modeling community

Accomplishments: Algae Harmonization Initiative

- Algal biofuel modeling has expanded in recent years, with inconsistent outcomes
- Prior TEA, LCA, and resource assessment (RA) modeling conducted by NREL, ANL, and PNNL was done independently (variations in inputs)
- Workshop held late 2011
  - Stakeholder representatives from industry, research, national labs
  - Goal: present algae models on TEA (NREL), LCA (ANL), and RA (PNNL) in order to:
    1) Harmonize models to common inputs
    2) Identify knowledge gaps
    3) Get stakeholder buy-in on assumptions and benchmark results
- Outcomes of workshop
  - Identified areas for harmonization, knowledge gaps, modeling uncertainties
    - Currently achievable growth rates?
    - Effects of seasonal variability?
    - Facility scale?
    - Requirement for liners?
    - Nutrient, water, carbon balances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Techno-economic analysis of autotrophic microalgae for fuel production

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ABSTRACT

It is well-established that microalgal-derived biofuels have the potential to make a significant contribution to the US fuel market, due to several unique characteristics inherent to algae. Namely, autotrophic microalgae are capable of achieving very high efficiencies in converting solar energy into biomass and oil relative to terrestrial oilseed crops, while at the same time exhibiting great flexibility in the quality of land and water required for algal cultivation. These characteristics allow for the possibility to produce appreciable amounts of algal biofuels relative to today's petroleum fuel market, while greatly mitigating

A National Resource Availability Assessment for Microalgae Biofuel Production

2009 Progress Report

Mark S. Wigmosta
André M. Coleman
Michael H. Huesemann
Richard Skaggs

October 2009

Pacific Northwest
NATIONAL LABORATORY

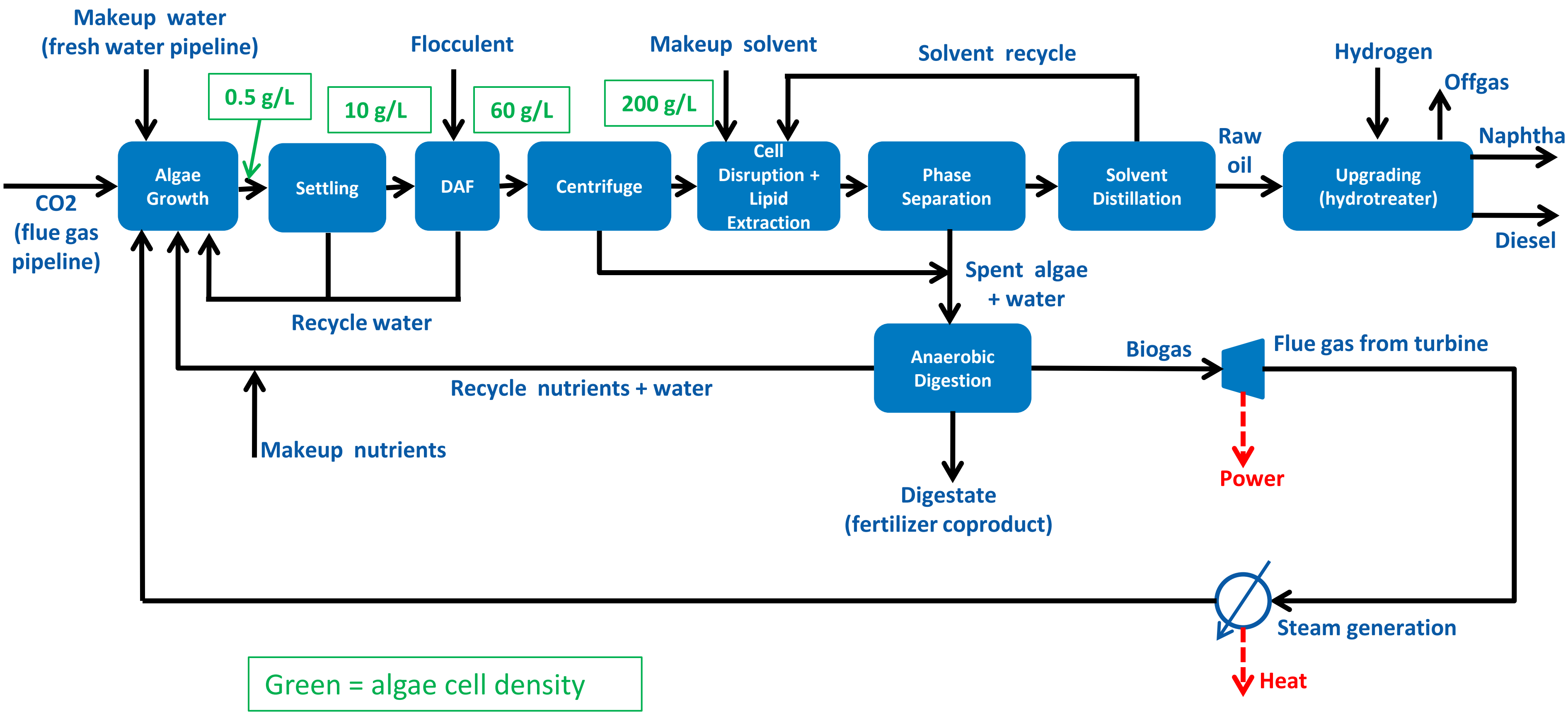
Argonne NATIONAL LABORATORY

ANL/ESD/11-5

Life-Cycle Analysis of Algal Lipid Fuels with the GREET Model

Energy Systems Division

Process Design Configuration (Harmonization)

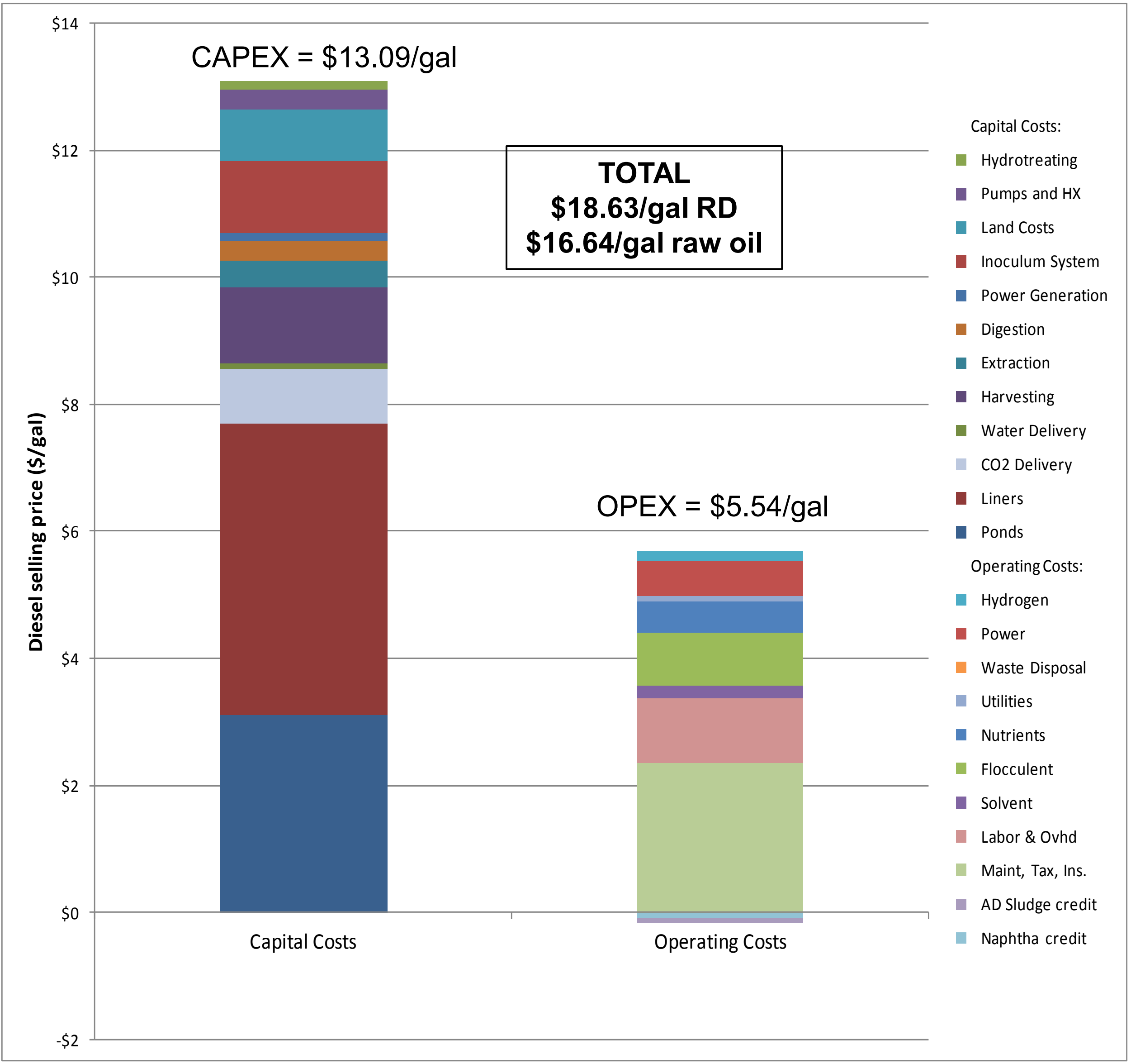


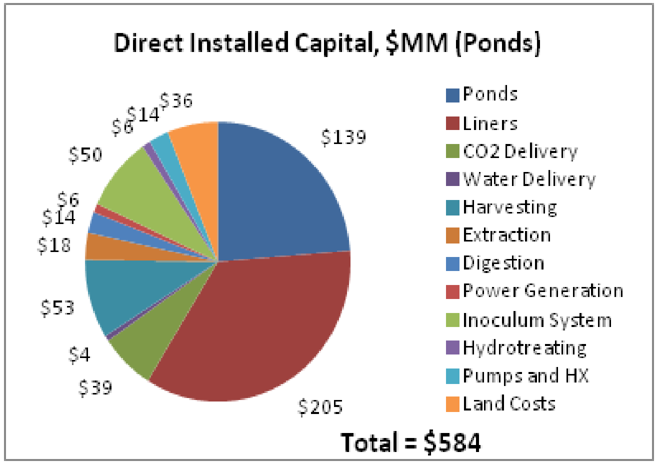
Design & Financial Assumptions

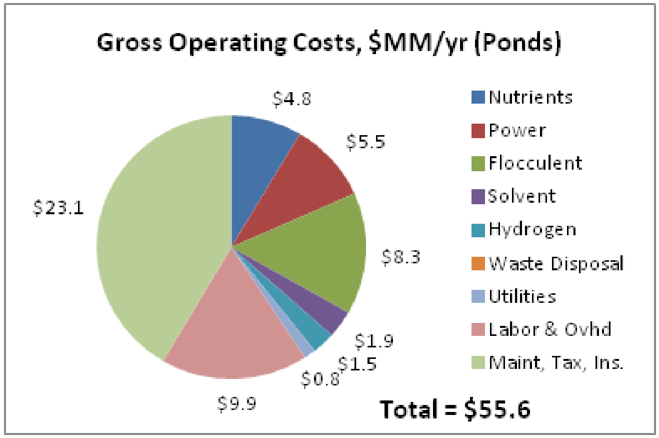
Design Assumptions (Cultivation)	Open pond baseline	
	Previous	**Harmonized**
Scale of system	10 MM gal/yr oil	10,000 acres (pond area)
Algae productivity [g/m^2/day]	25	Per site from RA
Algal cell density [g/L]	0.5	0.5
Lipid content [dry wt%]	25%	25%
Water evaporation rate [cm/day]	0.3	Per site from RA
Pond liners	No	Yes
CO_2 consumed [lb/lb algae]	1.9	2.0
N demand [algae composition, dry wt%]	8.7%	7.7%
P demand [algae composition, dry wt%]	1.3%	0.8%
Operating days/yr	330	330

Financial Assumptions	
Target internal rate of return (IRR)	10%
Cash flow methodology	Discounted cash flow rate-of-return (DCFROR)
Cost-year dollars	2007
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
Electricity prices	8 ¢/kWh (purchase), 6.5 ¢/kWh (credit)
Naphtha credit	$2.76/gal

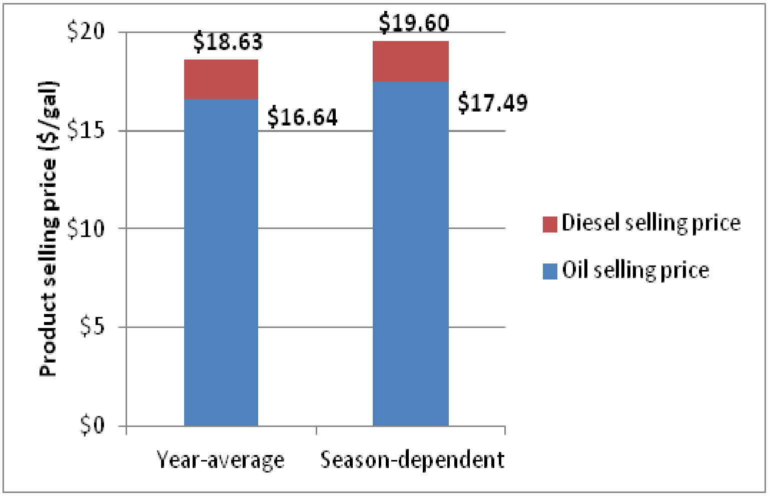
Harmonization Results: Year-Average (13.2 g/m²/day)

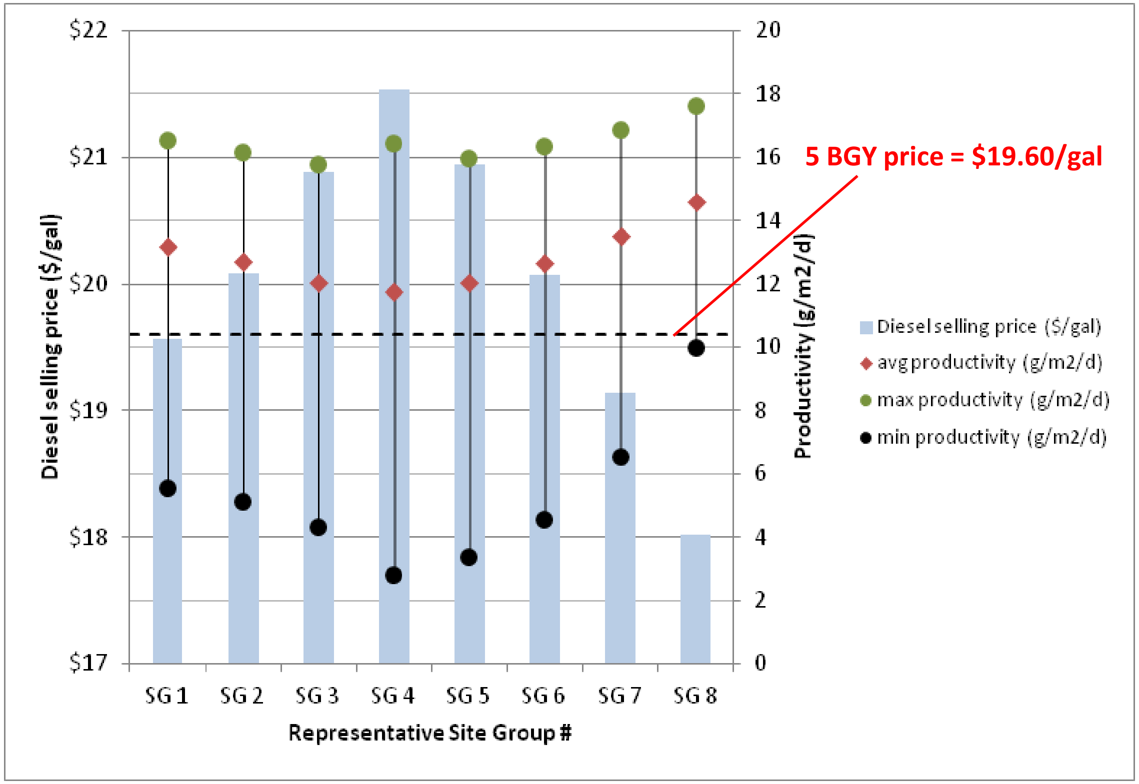






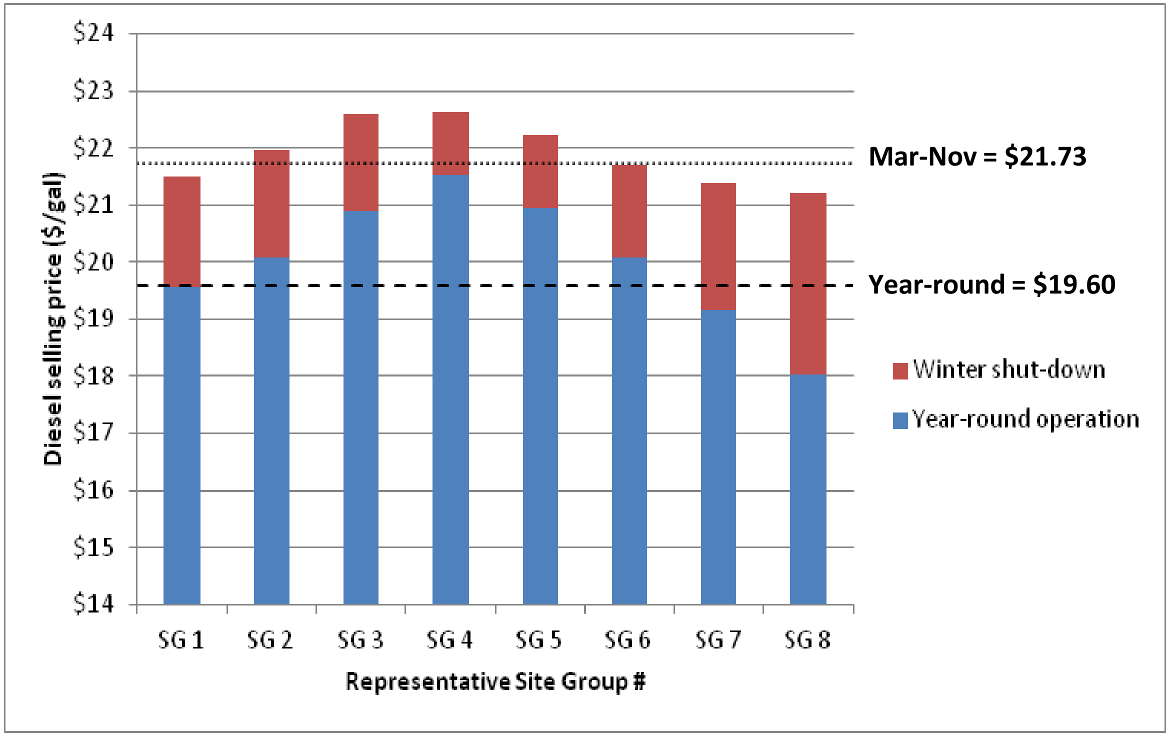
Harmonization Results: Seasonal Dependency





- Introducing seasonal variability adds ~$1/gal to cost
- High CAPEX dependency, poor utilization of installed capital at low productivity (primarily winter)
- Cost reduces as seasonal variability decreases
  - Site Group 4 = similar year-average productivity as SG 3 + 5 (higher in summer), but higher cost due to less efficient utilization of installed capital
  - SG 8 = $3.50/gal less than SG 4

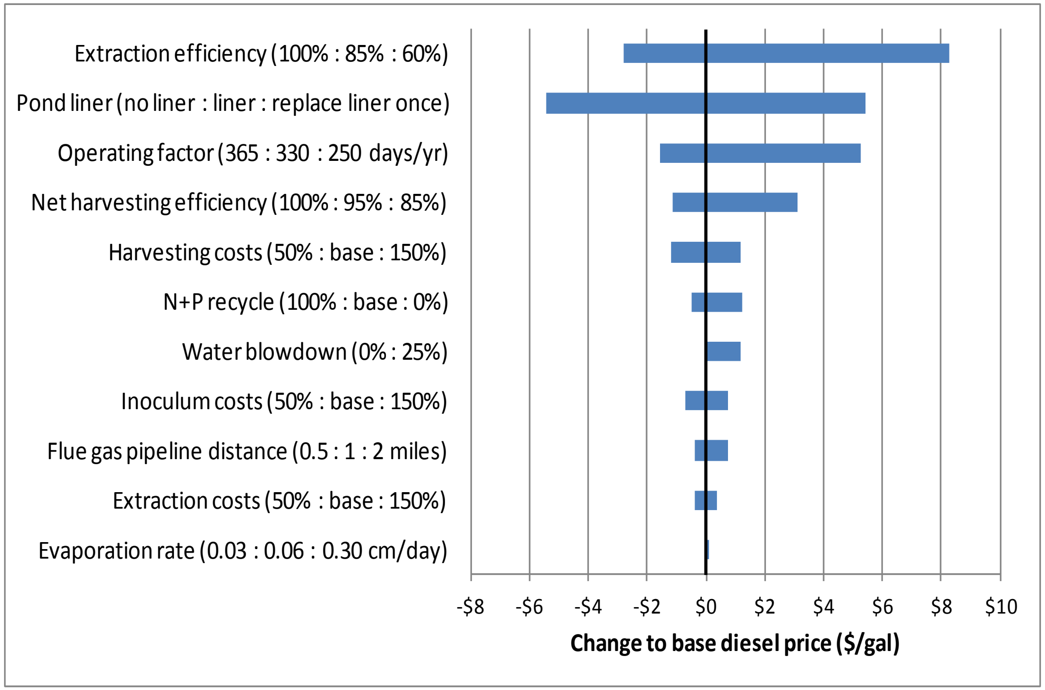
Results: Year-Round vs Winter Shut-Down



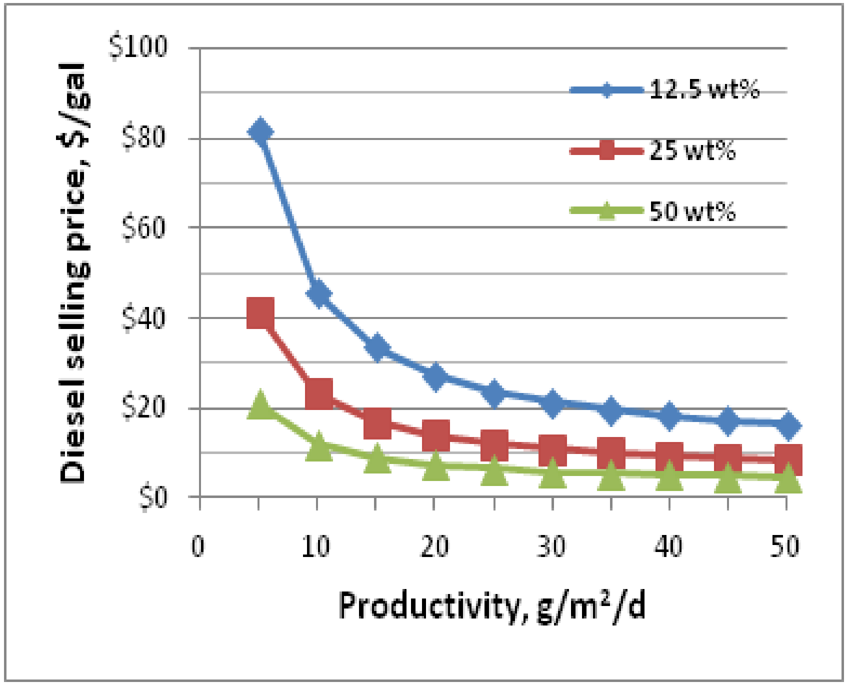
- $1.10-$3.20/gal price penalty (average ~$2/gal) for shutting down in winter vs year-round operation
- Variable OPEX = 11% of total cost
  - Savings in removing variable OPEX does not outweigh revenue lost during winter shut-down
- As long as ponds do not freeze in winter, economically beneficial to keep running even at 3-6 g/m^2/day (variance from LCA result)

Framing the Analysis

Tornado sensitivity plot (5 BGY baseline)



Yield Cost Curves



Relevance

NREL TEA modeling is highly relevant to DOE goals:

•Supports GREET (ANL) and BAT (PNNL) model interactions

•Helps to guide DOE decisions, out-year target projections
- *Technical targets (yields, process performance, etc)*
- *Cost targets*
- *Validation of modeling assumptions*

•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*

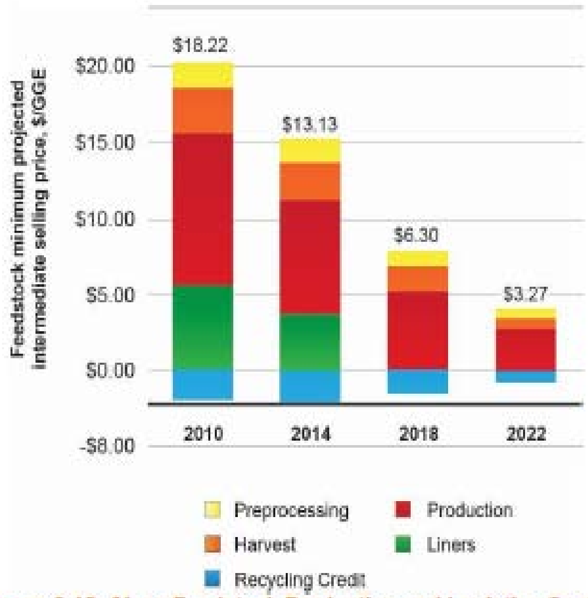


Figure 2-12: Algae Feedstock Production and Logistics Costs

Table 2-3: Algae Production and Logistics Costs for Lipid Extraction and Upgrading ($2011)

$2011		2010 SOT	2014 Projection		2018 Projection	2022 Target
Total Algal Feedstock Cost	$ / GGE Algal Oil	$18.22	$13.13		$6.30	$3.27
Production Cost	$ / GGE Algal Oil	$15.60	$11.18		$5.17	$2.63
Harvest Cost	$ / GGE Algal Oil	$2.99	$2.52		$1.65	$0.67
Preprocessing Cost	$ / GGE Algal Oil	$1.72	$1.56		$1.11	$0.77
Recycle Credit	$ / GGE Algal Oil	-$2.08	-$2.14		-$1.63	-$0.80

From November 2012 MYPP:
http://www1.eere.energy.gov/biomass/pdfs/mypp_november_2012.pdf

Success Factors

Success Factors:

- Maintaining close interaction with researchers is crucial
- Transparent communication of all assumptions and results to ensure proper use of data
- Buy-in from all stakeholders is critical
- Leverage TEA to assist in algae process development and research decisions (not only “analysis for the sake of analysis”)

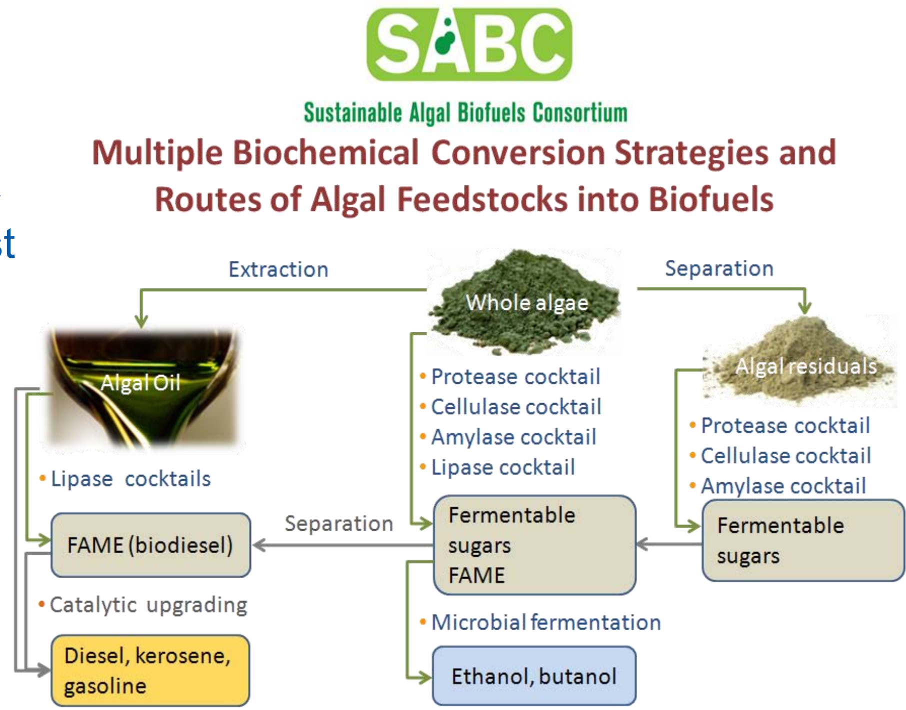
Challenges:

- Validate algae growth and oil productivity rates based on meaningful, sustained data from large scale demonstrations
  - High priority for current and future consortia work (NAABB, SABC, ATP^3, FY13 ABY FOA)
- Further evaluate design requirements for pond liners
  - Critical cost factor in overall TEA results
  - Will be driven by local regulatory policies, soil/strain characteristics
- Reduce cost and increase efficiency of dewatering/extraction steps
- Better characterization of raw oil and upgrading requirements
- Further evaluate co-product opportunities

**Supporting context provided in: http://www.nrel.gov/docs/fy13osti/58049.pdf*

Future Work

- Continue to improve and refine baseline model assumptions
  - Working with an engineering subcontractor to develop vendor-supplied design and cost estimates for key equipment
- Evaluate data from research partners for new/ developing technologies
  - NAABB (dewatering alternatives)
  - SABC (biomass fractionation + conversion to multiple fuel products)
  - NREL/WSU partnership (AD performance for algal residues)



- HTL harmonization (FY13)
  - Work has begun on a new harmonization analysis for algal biofuel production via HTL processing (leverage PNNL experimental data)
  - Partners: ANL (LCA), PNNL (Resource Assessment + TEA)
  - Deliverable: Joint HTL Harmonization Report, Fall 2013
- ALU design case (FY14)
  - Build on FY12 harmonization for ALU (algal lipid upgrading) pathway
  - Incorporate vendor costs, subcontractor design information, partner R&D data
  - Deliverable: ALU Design Report, Fall 2014

Summary

- NREL Algae TEA task has made important achievements in FY12-13
  - Harmonization improved consistency of models to “tell the same story” on TEA, LCA, and RA outcomes for near-term benchmarks
  - Site and seasonal-explicit models highlight important implications for commercial operation, site selection, tradeoffs to consider with LCA
  - Support DOE MYPP efforts (baseline + out-year target projections)
  - Support broader algae community (transparent, rigorous models; quantify R&D improvements)
- Current models suggest a large potential for cost reduction
  - Yield improvements are critical (13.2 g/m^2/day + 25% lipid = 1,100 gal/acre/yr, realistic potential for ~5-fold improvement)
  - Scenario analysis suggests viable pathways exist to $3/gal through yield improvements, engineering cost reductions, and co-product opportunities
- Considerable activity planned for FY13-14
  - HTL harmonization
  - Expand on ALU pathway model
  - Further investigate SABC “fractionation” pathway
    - Early analysis suggests potential for significant cost reduction given increased BTU yield to fuels
  - Collaboration with new ATP^3 consortium
    - Expand and exercise current models to reflect performance demonstrated in multi-region algae test-beds


NREL, Sept, 2010, Pic #18229

Questions?

Acknowledgements

• Thank you to…

- Bioenergy Technologies Office Algae Team (Valerie Sarisky-Reed, Daniel Fishman, Christy Sterner, Kristen Johnson, Christine English, Joyce Yang, Zia Haq, Alicia Lindauer)
- NREL researchers: Christopher Kinchin, Mary Biddy, Steve Phillips, Ling Tao, Phil Pienkos, Lieve Laurens, Nick Nagle, Eric Jarvis, Adam Bratis
- National Laboratory Partners (ANL, PNNL, INL, ORNL, SNL)
- Consortia Partners: NAABB (Meghan Starbuck Downes), SABC (Gary Dirks), ATP^3 (Gary Dirks)
- Industrial Partners

Additional Slides

Responses to Reviewers' Comments from 2011

•Modeling is still too removed from actual application. Need to integrate modeling with the consortium projects.

•We have made it a priority during FY13 project management planning to include a deliverable for evaluation of data made available from partner consortia and other research projects for NREL's Aspen models. While such data took some time to generate (typically TEA lags behind research activities which must first generate the data), information has recently been made available from NAABB, SABC, and Washington State University partnerships, and NREL is currently working through incorporation of these data into the models.

•Coordination with other efforts on LCAs and technoeconomic assessments should be exploited to maximize benefits.

•A primary achievement made since the 2011 peer review was the harmonization analysis described in this presentation, which was a rigorous and highly detailed modeling effort done in coordination with PNNL (Resource Assessment) and ANL (Lifecycle Analysis). Additionally, the NREL TEA modeling team works with a number of other TEA/economic analysis teams, including those within the NAABB consortium (primarily the Texas A&M modeling effort led by Dr. James Richardson).

•The use of dissolved air flotation and chemical coagulation is unrealistic and will need to be substituted for low-cost, low energy intensity technologies … Transparency and ability to modify the assumptions should continue to be emphasized.

•The current baseline model was established primarily to serve as a benchmark, using established well-known technologies (including the use of DAF, a widely-utilized operation in wastewater processing), and to allow for evaluation of alternative technologies currently under development for algal processing. While data in the public domain for such novel algal dewatering technologies is still scarce, a number of options are being investigated by consortia groups, and these data are currently being evaluated in NREL's models. Two such examples include the use of electrocoagulation and membrane dewatering.

Publications and Presentations

Publications:

•Davis, R.; Aden, A.; Pienkos, P.T. (2011). "Techno-economic analysis of autotrophic microalgae for fuel production." *Applied Energy* (88); pp. 3524-3531.

•Sun, A.; Davis, R.; Starbuck, M.; Ben-Amotz, A.; Pate, R.; Pienkos, P.T. (2011). "Comparative cost analysis of algal oil production for biofuels." *Energy* (36); pp. 5169-5179.

•Davis, R.; Fishman, D.; Frank, E.D.; Wigmosta, M.S.; Aden, A.; Coleman, A.A.; Pienkos, P.T.; Skaggs, R.J.; Venteris, E.R.; Wang, M.Q. (2012). "Renewable diesel from algal lipids: An integrated baseline for cost, emissions, and resource potential from a harmonized model." *ANL/ESD/12-4; NREL/TP-5100-55431; PNNL-21437.*

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

•Davis, R.; Biddy, M.; Jones, S. (2013). "Algal lipid extraction and upgrading to hydrocarbons technology pathway." *NREL/TP-5100-58049; PNNL-22315*. http://www.nrel.gov/docs/fy13osti/58049.pdf, http://www.pnl.gov/main/publications/external/technical_reports/PNNL-22315.pdf

•Biddy, M.; Davis, R.; Jones, S.; Zhu, Y. (2013). "Whole algae hydrothermal liquefaction technology pathway." NREL/TP-5100-58051; PNNL-22314. http://www.nrel.gov/docs/fy13osti/58051.pdf, http://www.pnl.gov/main/publications/external/technical_reports/PNNL-22314.pdf

Presentations:

•Davis, R.; Aden, A. (2011). "Techno-economic analysis of microalgae-derived fuel production." 33rd Symposium on Biotechnology for Fuels and Chemicals; Seattle, WA

•Davis, R.; Aden, A. (2011). "Techno-economic analysis of microalgae-derived fuel production." 2011 Algae Biomass Summit; Minneapolis, MN

•Aden, A.; Davis, R.; Pienkos, P.T. (2011). "Algal biofuel pathway baseline costs." DOE Algae Harmonization Workshop; Tucson, AZ

•Pienkos, P.; Aden, A. (2012). "Forum: Algal biofuels modeling: Planning for a viable industry." World Renewable Energy Forum; Denver, CO

•Davis, R.; Aden, A.; Pienkos, P.T. (2012). "Integrated algal biofuel baseline analysis: Techno-economics from a harmonized model." 2012 Algae Biomass Summit; Denver, CO

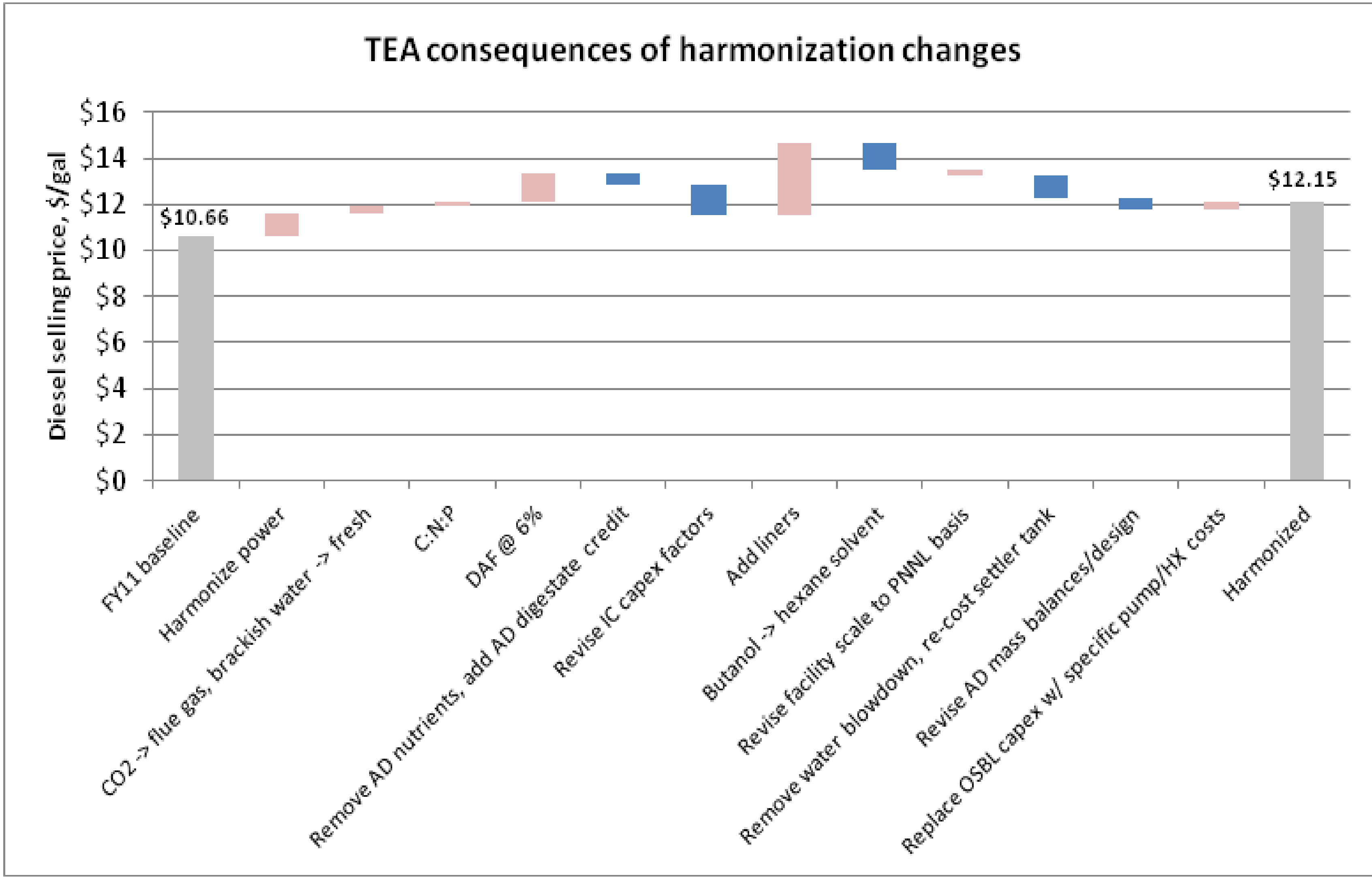
Backup Slides

Algae TEA Task Milestones

Task Milestones/Activities	FY13											
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Algal Lipid Upgrading (ALU) pathway work												
Incorporation of data for developing technologies (Includes leveraging available data from NAABB/SABC consortia)						▼						
Baseline ALU cost model development (Includes incorporation of consortia data + vendor design info)									▲			
Algal Hydrothermal Liquefaction (HTL) pathway work												
FY13 HTL harmonization project management plan				▶								
HTL harmonization (Develop harmonized models + HTL report)										▼		▲
	FY14											
Algal Lipid Upgrading (ALU) design case development												
FY14 milestones have not yet been developed												

▲= NREL D-milestone, ▶ = NREL E-milestone, ▼ = Deliverable

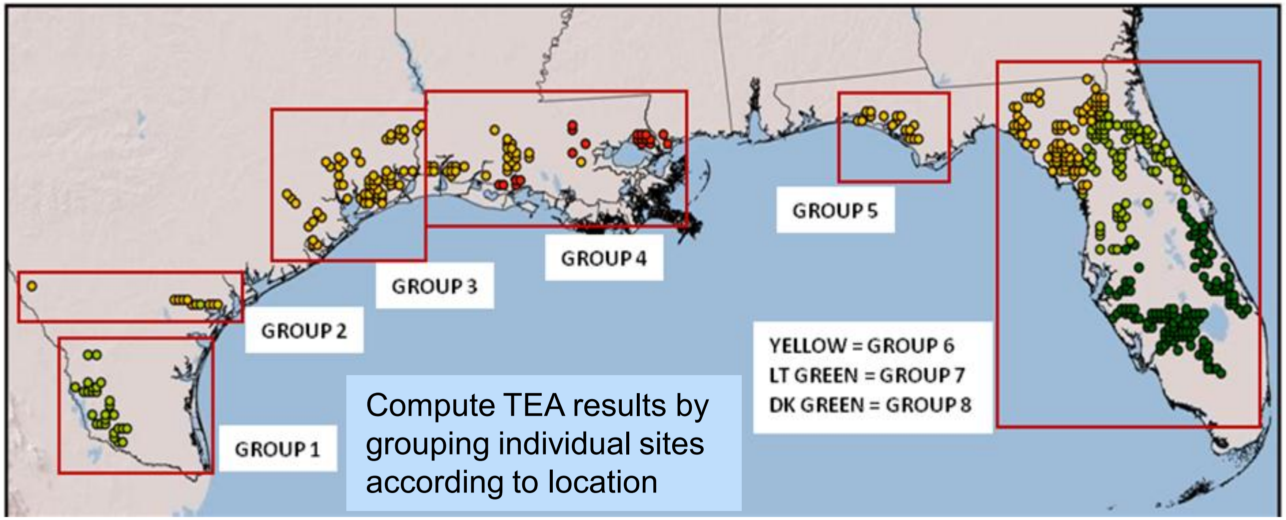
Effect of TEA/LCA Harmonization on TEA at 25 g/m²/day



*Details for each step change are skipped in this brief talk; refer to harmonization report for further information (http://www.nrel.gov/docs/fy12osti/55431.pdf)

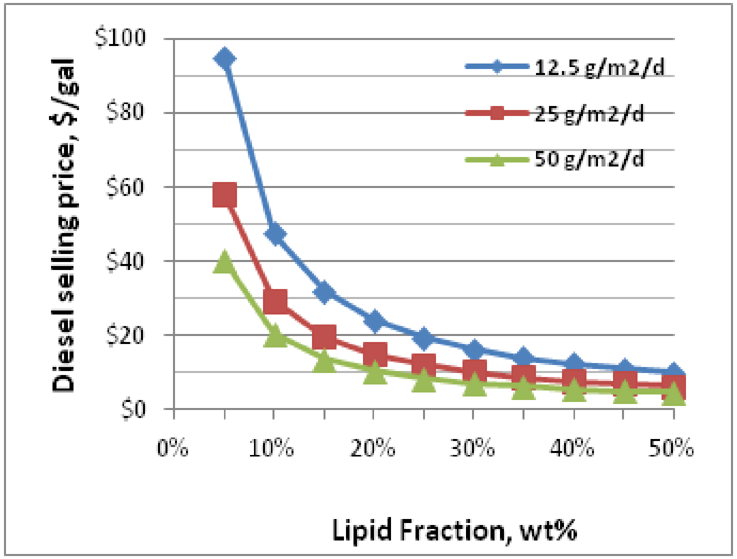
Harmonization with RA: Results for 5 BGY Scenario

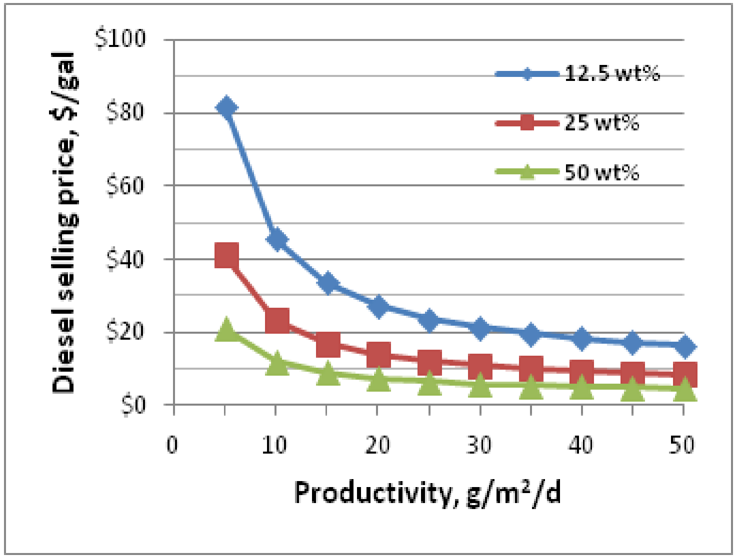
- Consider season and location explicitly in harmonized LCA/TEA
- Group 450 sites into representative "site groups" for manageable number of TEA Aspen runs
- Set facility scale design capacity based on maximum productivity season for each group



Site Group	# of Sites in Group	Productivity, $g/m^2/day$				Net Water Loss (Evaporation-Precipitation), cm/day			
		Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring
1	27	**16.6**	14.0	5.5	16.5	0.5	0.16	0.09	0.37
2	11	15.8	13.6	5.1	**16.2**	0.36	0.12	0.03	0.21
3	60	14.8	13.2	4.3	**15.8**	0.17	0.05	0.002	0.06
4	49	**16.5**	12.6	2.8	15.0	0.04	0.01	0.001	0.02
5	16	**16.0**	12.9	3.4	15.9	0.03	0.004	0.001	0.04
6	77	**16.3**	13.5	4.5	16.2	0.04	0.01	0.003	0.08
7	82	16.1	14.4	6.5	**16.9**	0.05	0.01	0.01	0.11
8	124	15.4	15.4	10.0	**17.6**	0.03	0.01	0.02	0.15
Total weighted average		**13.2**				**0.06**			

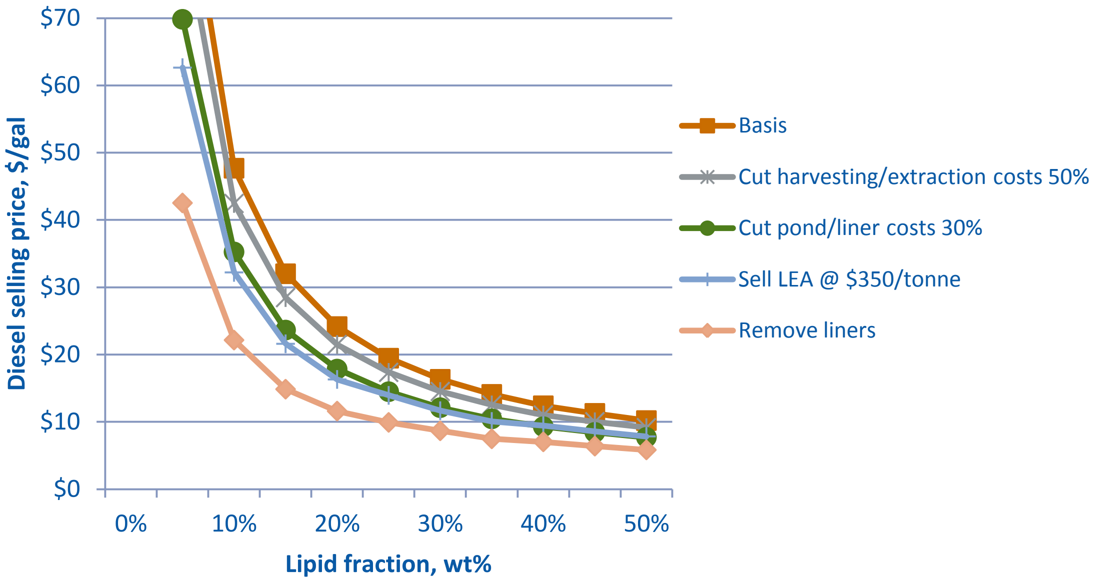
Harmonization: Nonlinear Response





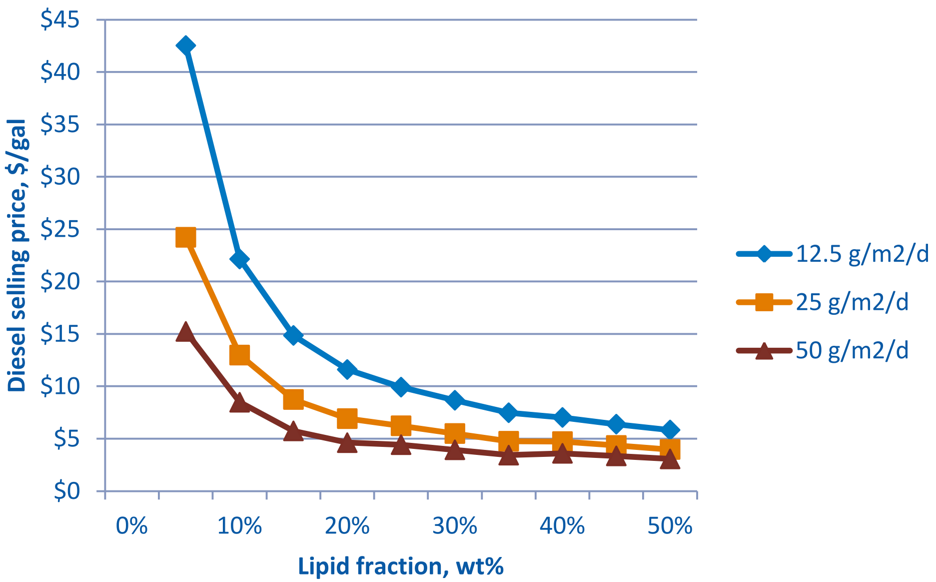
- Similar to LCA results, TEA exhibits high cost sensitivity to lipid content and productivity at values < 20% or 20 $g/m^2/d$
  - Baseline at 13.2 $g/m^2/d$ = unstable portion of curve (higher error margin)
- Lipid content exhibits stronger cost impact than productivity
  - Key result for R&D: more “bang for the buck” increasing lipids

Alternative scenarios: projecting cost improvements



Four alternatives at 12.5 g/m^2/day

- Combination of all improvements reduces selling price nearly 50% at >25% lipid
- Note, LEA @ $350/tonne gives nearly the same coproduct credit as AD



Improved scenario at 12.5-50 g/m^2/day

- Combination of all improvements above
  - 12.5 g/m2/day = $5.83/gal
  - 25 g/m^2/day = $3.97/gal
  - 50 g/m^2/day = $3.07/gal