GREET for Algae Life Cycle Analysis

WBS 9.6.5.2

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Algae Technology Area

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

Goal Statement

- Determine reduction in GHG emissions and fossil energy use when algal biofuels replace petroleum fuels.

- "Support program decisions by establishing basis of quantitative metrics" - MYPP

Abbreviations

- AD – Anaerobic digestion
- HTL– Hydrothermal liquefaction
- LE– Lipid extraction pathway
- TEA – Techno-economic analysis
- RA – Resource assessment
- WTP – "Well to pump," i.e., production portion of life-cycle
- PTW – "Pump to wheel," i.e., fuel-use portion of life-cycle
- WTW – "Well to wheel," i.e., whole life-cycle, WTP plus PTW.

Quad Chart Overview

Timeline

- Project start date: 7/01/09
- Project end date: Annual
- Percent complete: On schedule

Budget

- Total project funding: $1,300k
  - DOE share: 100%
  - Contractor share
- Funding for FY12: $400
- Funding for FY13: $375
- ARRA Funding: $0k

Barriers

- Barriers addressed
  - St-D: Indicators and methodology for evaluating sustainability.
  - At-A: Lack of comparable, transparent, reproducible analysis
  - At-C: Inaccessibility and unavailability of data.

Partners

- Several community in-kind partners, e.g.,
  - NAABB
  - NREL (TEA)
  - PNNL (Resource assessment)

Project Overview- Context

- Address sustainability of algal biofuels
- Life Cycle Analysis (LCA) assesses sustainability via:
  - Greenhouse gas emissions, petroleum displacement, fossil energy use, and criteria pollutants.
- Challenges for algae LCA:
  - Algal fuel production pathways are not mature
  - Many scenarios and possibilities
  - Lack of validated data, much data proprietary

Project Overview- Objectives

Objective
1. Enable consistent comparison between algal and other fuels
2. Determine GHG and energy usage results for selected algae pathways
3. Improve algae LCA methodology
4. Inform economic assessment and process development
5. Develop tools and methods for use across the program and across the algae community

1 - Approach

Management

- Work with BETO for annual priorities and goals
  - Annual operating plan has objectives, deliverables, & milestones

Technical

- Extend GREET for algae
  - Ensures comparability with other fuels and with other BETO biofuel LCAs, and ensures completeness of upstream treatments.
- Iterative development: Update data, GREET, and LCA
  - Start with literature, including older ASP and other reports
  - Engage community including DOE algae consortia
- Harmonize with TEA and resource assessment

Unique Aspects

- GREET provides BETO with uniform results between algae and hundreds of other fuel production pathways

2 - Accomplishments - Summary

- 4/11 – Previous review
- 8/11 – Argonne technical report for lipid extraction pathway
- 3/12 – *ERL* paper: Importance of AD and N2O
- 5/12 – *MITI* paper: Hydrothermal Liquefaction
- 6/12 – “Harmonization” report combing LCA, TEA, & RA
- 9/12 – Two internal reports: Infrastructure materials and AD
- 3/13 – *Alg. Res.* paper submitted re Nutrients LCA
- 3/13 – *ES&T* paper submitted re AD emissions
- *Alg. Res.* paper re infrastructure materials nearly complete

See additional slides at end for technical details excluded from the main presentation for sake of time.

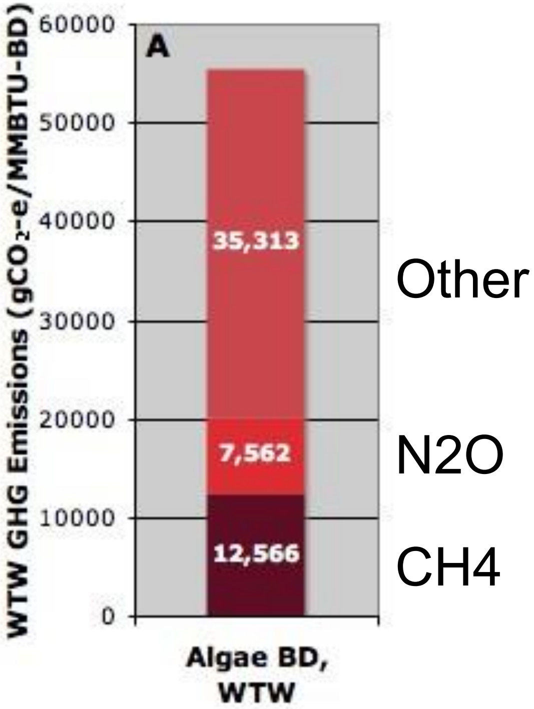
2 – Accomplishments

See additional slides at the end of this file for technical details of the system definition and system boundary that were excluded from the main presentation for sake of time.

The following slides focus a few technical results and showing their tie-in to the BETO Algae Technology objectives

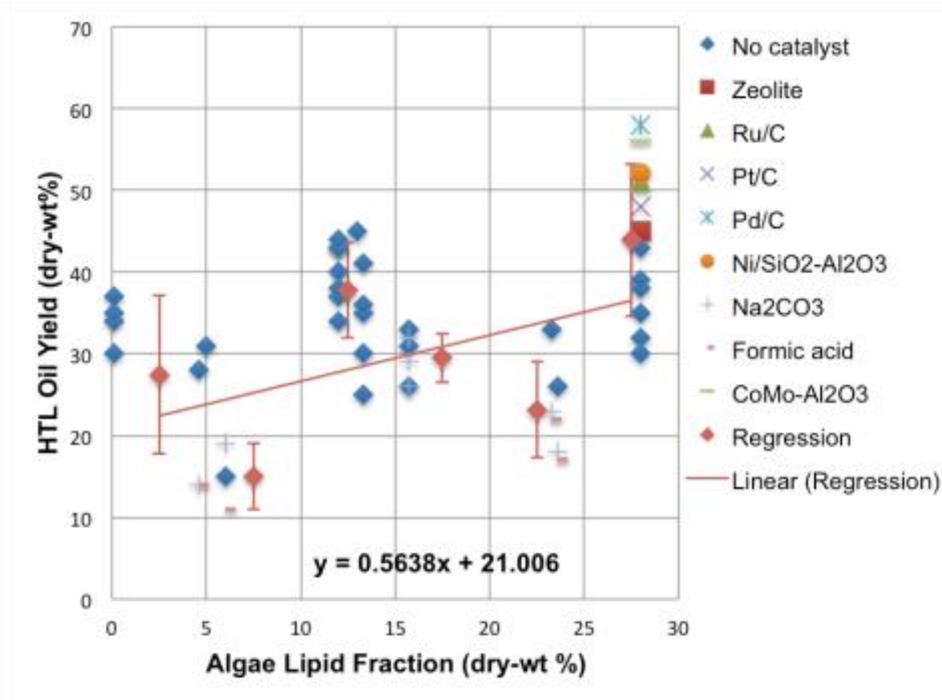
2 – Biodiesel: Technical Report & ERL Paper

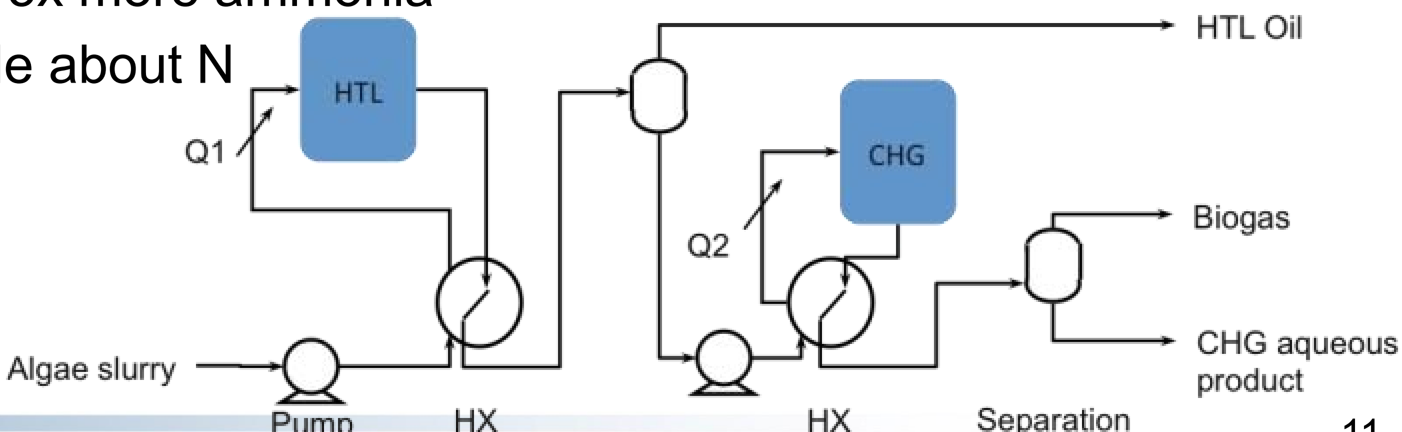
- Biodiesel from extracted lipids
  - See extra slides for system definition
  - GHGs 55% that of petroleum diesel
  - Not definitive: Many uncertainties
- Accompanied by GREET release
  - Full transparency of analysis and data
  - APD tool enables easy modification by others
- Key issues identified:
  - Fugitive CH4 from AD
  - Must account for fate of all N
    - N2O from digestate applied to fields
  - Accurate treatment of recycling residuals for energy, N, & P is essential
- ERL paper selected for Editors' 2012 highlights



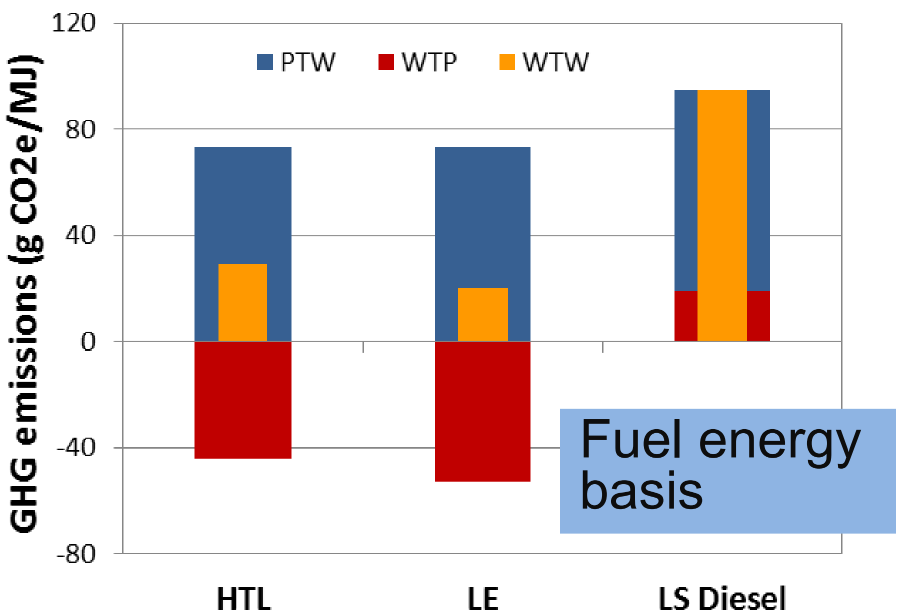
2 – Renewable Diesel from Hydrothermal Liquefaction- MITI Paper

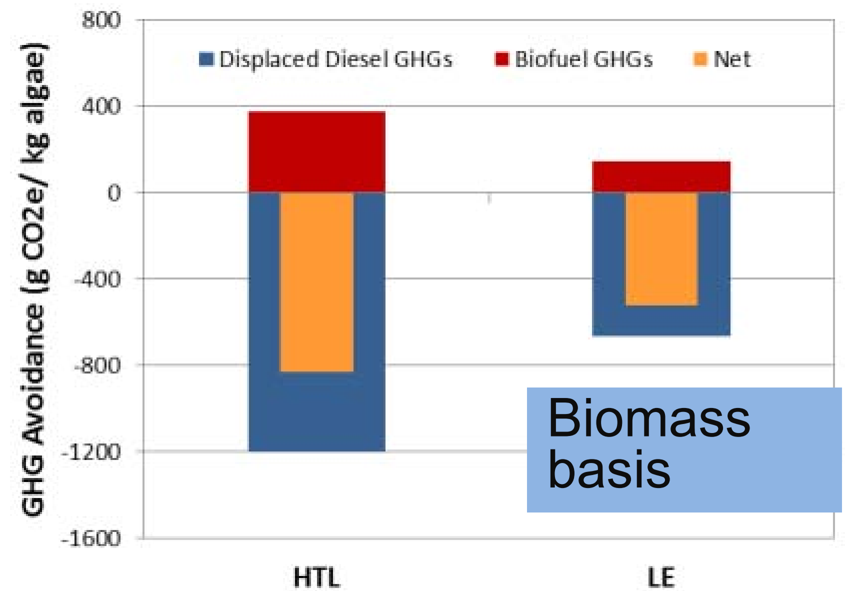
- Model via comprehensive review
  - Diverse yields in literature
  - Significant N in oil
  - No clear data for hydrotreatment
- Key issues identified:
  - N in aqueous phase challenging for AD
  - HTL required only 54% of the biomass as did LE
  - HTL required 5x more ammonia
  - See extra slide about N





2 – Renewable Diesel from HTL - MITI Paper

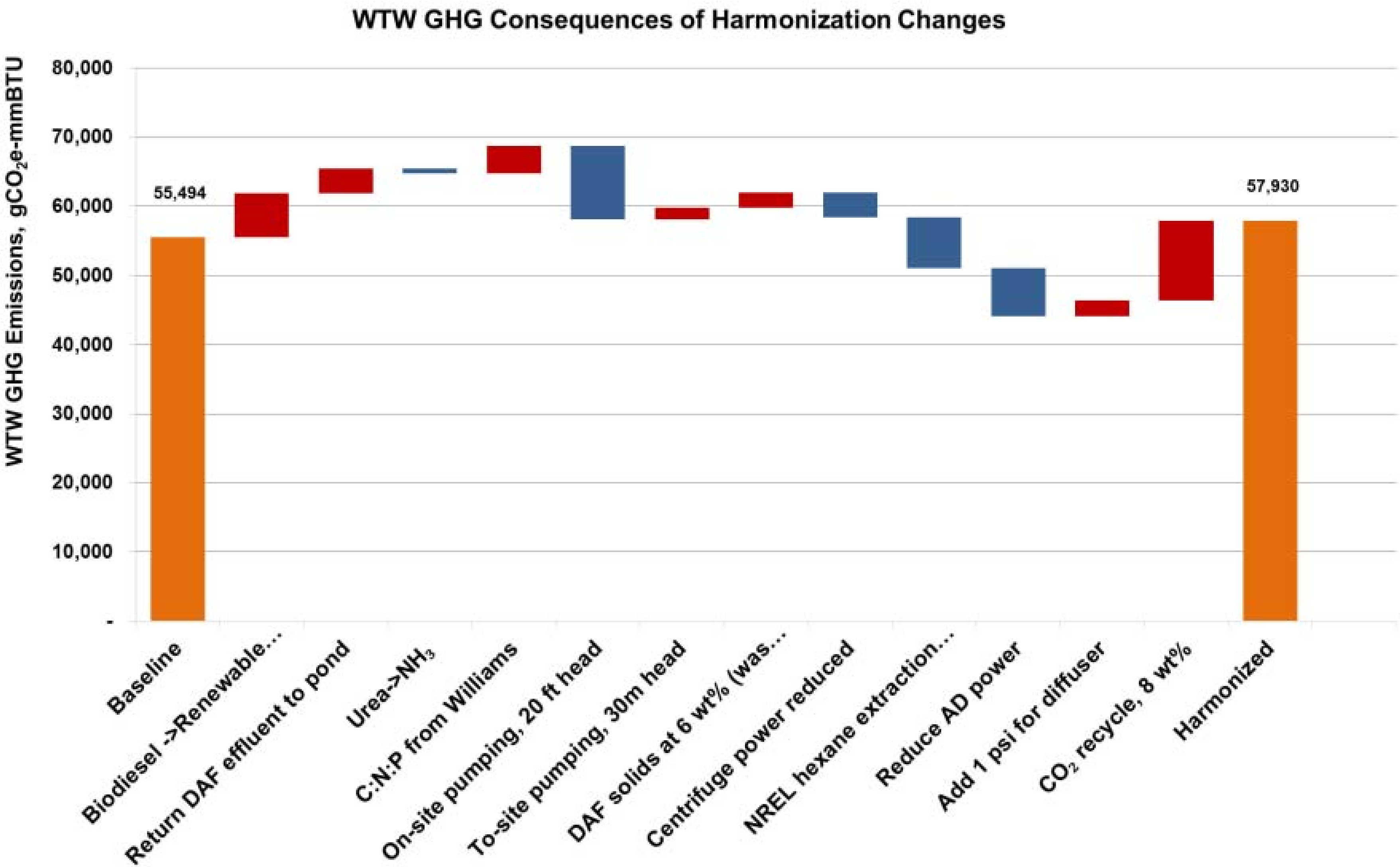




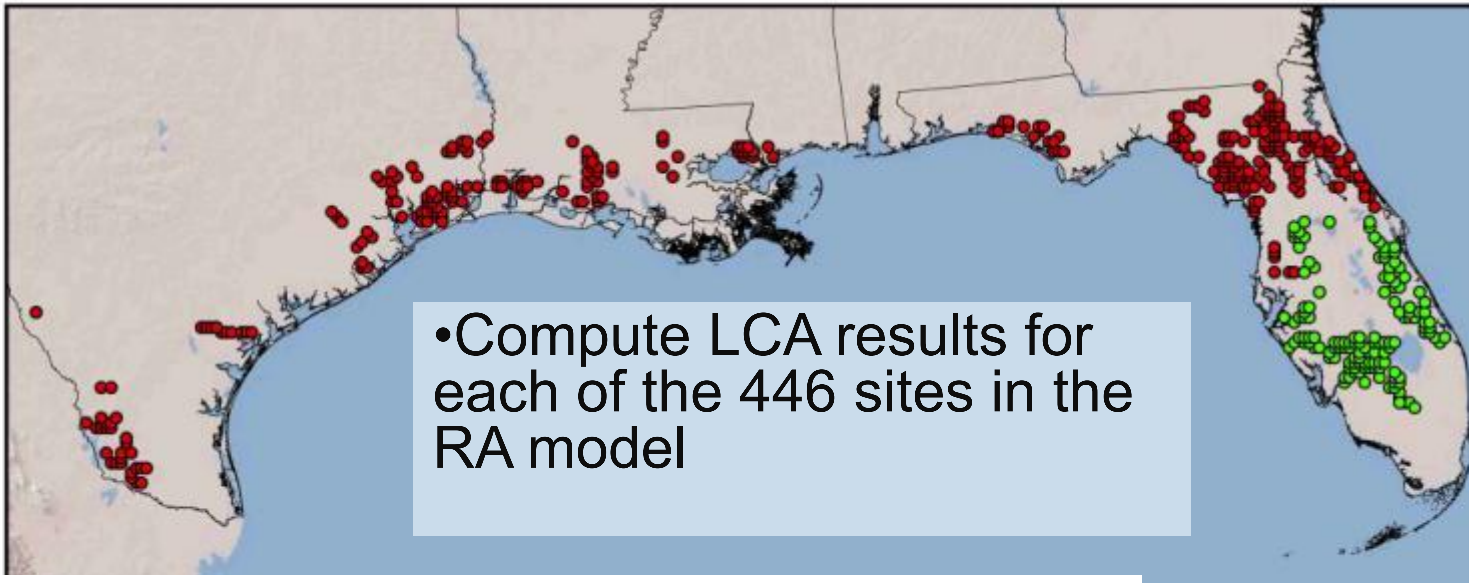
- Lower GHG emissions for LE pathway per unit of fuel
- Higher biopower from LEA reduces grid electricity for LE

- HTL makes more fuel per unit of biomass
- If biomass is limiting resource, HTL has greater potential for GHG avoidance despite higher GHGs per unit fuel.

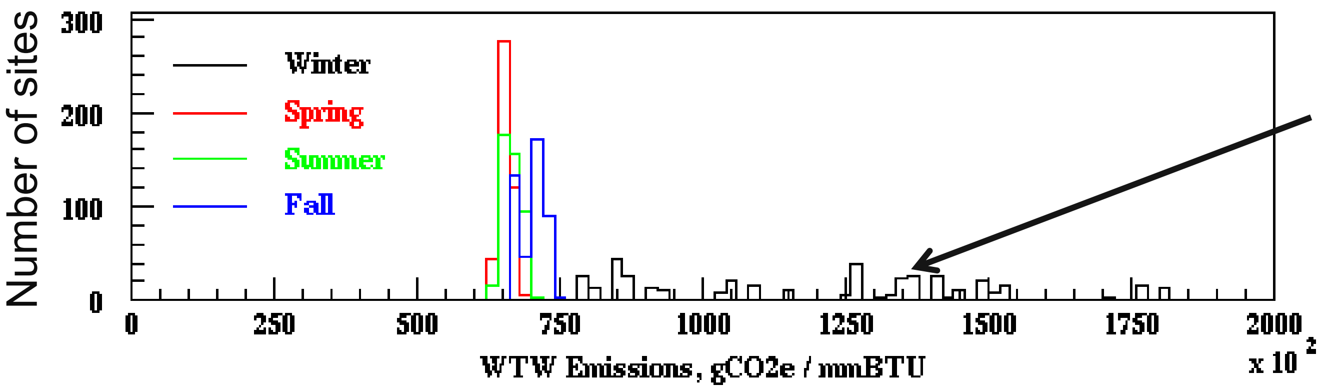
2 – Harmonization with TEA Considered Many Parameters



2 – Harmonization with RA: 5 BGY Scenario



•Compute LCA results for each of the 446 sites in the RA model



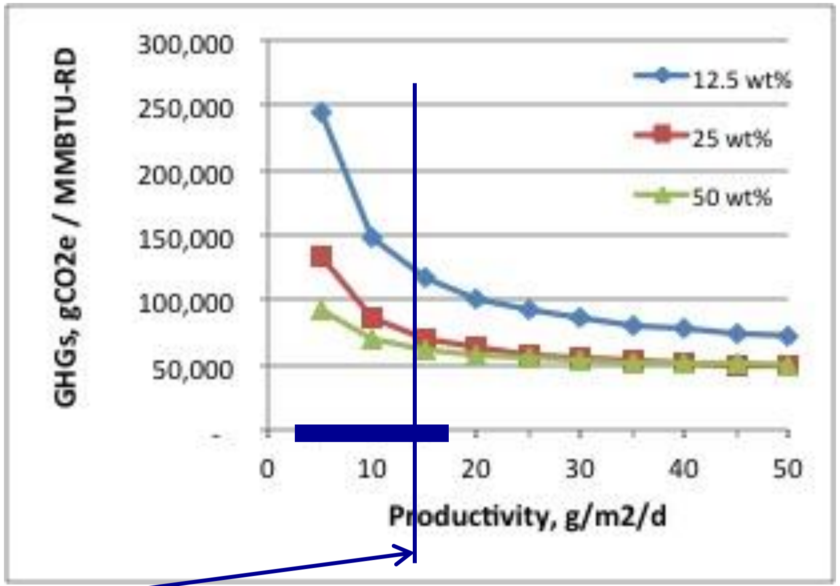
Large winter emissions for some sites

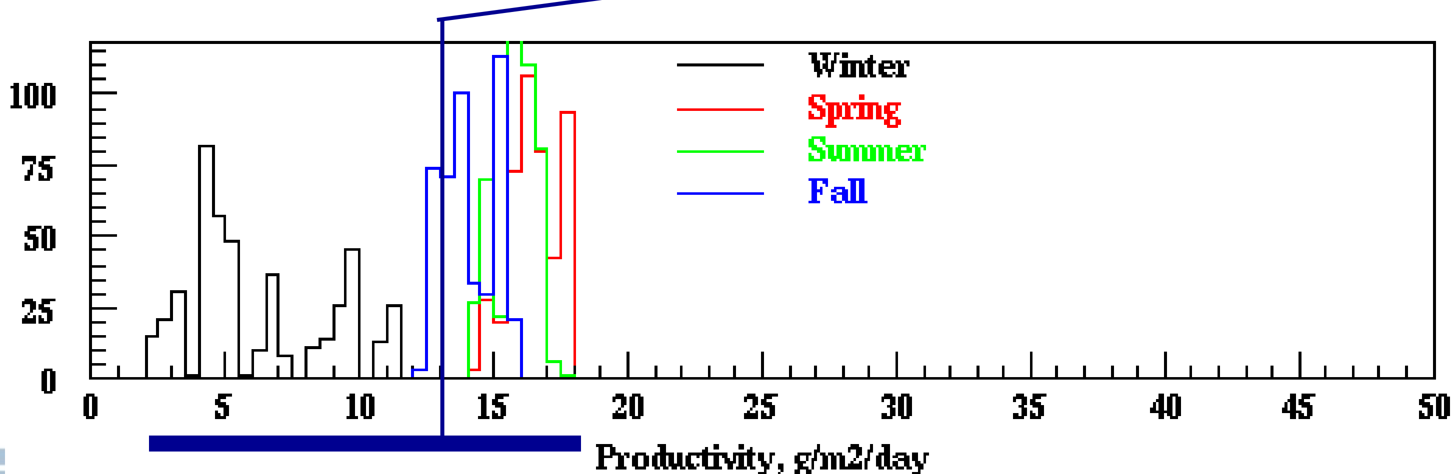
•Spring, summer, fall, averaged over all sites:

WTW Quantity	Result	Units
Fossil energy consumption	0.68 ± 0.02	BTU / BTU-RD
Petroleum energy consumption	0.106 ± 0.002	BTU / BTU-RD
Total energy consumption, including renewable	3.4 ± 0.03	BTU / BTU-RD
GHG emissions (without winter)	67,400 ± 2,000	gCO_2e / MMBTU-RD

2 –Nonlinear Response Affects Uncertainty

- Nominal productivity is near steep slope
  - Slope translates uncertainty in productivity into amplified uncertainty in GHG emissions
  - Must improve winter and fall performance
  - Lipid curve is similar





3 –Relevance of GREET Algae LCA for BETO Algae Program

- Assessed algae sustainability (GHG emissions and energy use)
  - For conservative assumptions, 50% reduction is challenging
- Analyzed and helped define the core algae pathways for BETO
  - Peer reviewed LCA publications for extraction and HTL pathways
  - Defines reference model for evaluating progress and alternatives
- Guides experimental process development and pathway definition
  - LCA motivated new ARID scale-up model with 2x less mixing energy
  - High winter emissions indicate a biology / cultivation technical gap
    - Shift discussions away from peak and average productivity!
    - Seasonal shut-down inconsistent with TEA and AD

3 –Relevance of GREET Algae LCA for BETO Algae program

- Defines key LCA issues and improves algae LCA methodology. Examples include
  - Handling of process residuals key to all pathways
    - Energy recovery from residuals to avoid grid electricity
    - Issues centering on combined heat and power / process integration
    - Must include fate of all (unstable) C and N
    - Must control fugitive methane emissions
  - Must understand fate of N incorporated into HTL oil
  - Must consider seasonal variation
- Transparent, public platform for algae LCA analysis

4 - Critical Success Factors Affecting Analysis Risk

Risk	Mitigation Approach
Algal fuel production pathways are theoretical and not clearly defined	• Develop process models to explore system • Sensitivity studies
Quality & availability of process data	• Build relationships with algae R&D consortia • Use harmonization process to vet • Community can share and contribute data via our“integration framework” approach.
Large number of scenarios	• Seek general principles while pursuing core BETO algae pathways • Provide tool that rapidly generates GREET model inputs from the LCI to support broad analysis community

5. Future Work

- Complete analysis of NAABB technology
- Continue and expand harmonization work including emerging data from DOE consortia and labs
  - Example: HTL data from PNNL
- Pursue alternative pathway definitions
- Evaluate more aggressive assumptions
- Continue to support algae LCA in the community via public release of GREET tools

Summary

- The objectives are relevant to BETO's Algae Technology Area by examining whether the BETO pathways can achieve petroleum use reduction and GHG reduction targets. Also, improving LCA methods.
- The approach is effective by providing transparency through detailed technical reports and public release of the tools, by enabling analysis by the algae community, and by utilizing the emerging data from the DOE consortia to understand the LCA implications of algae technology
- The work has many technical accomplishments. Examples were given of how these results can inform the experimental program
- Future work is determined in collaboration with BETO and focuses on BETOs highest priority questions each year
- Success (risk) factors were identified along with risk mitigation strategies. The largest risk is availability of data.
- Technology transfer is achieved through public releases of GREET.

Questions?

Additional Slides

(Not a template slide – for information purposes only)

- *The following slides are to be included in your submission for Peer Evaluation purposes, but <u>will **not** be part of your Oral presentation</u>*
- *You may refer to them during the Q&A period if they are helpful to you in explaining certain points.*

GREET Computes Energy Use and Emissions for More Than 100 Fuel Production Pathways from Various Feedstocks

- **Petroleum**
  - Conventional
  - Oil Sands

→

- Gasoline
  Diesel
- Liquefied Petroleum Gas
- Residual Oil (to electricity)
- Jet Fuel

- **Natural Gas**
  - North American
  - Shale Gas
  - Non-North American

→

- Compressed Natural Gas
  Liquefied Natural Gas
- Liquefied Petroleum Gas
- Hydrogen
- Methanol
- Dimethyl Ether
- Fischer-Tropsch Diesel
- Fischer-Tropsch Jet Fuel

- Corn

→

- Ethanol
- Butanol

- Sugarcane

→

- Ethanol

- Soybeans

→

- Biodiesel
- Renewable Diesel
- Renewable Gasoline
- Renewable Jet Fuel

- Coke Oven Gas
- Petroleum Coke
- Nuclear Energy

→

- Hydrogen

- Coal

→

- Hydrogen
- Methanol
- Dimethyl Ether
- Fischer-Tropsch Diesel
- Fischer-Tropsch Jet Fuel

- **Renewable**
- **Natural Gas**
- Landfill Gas
- Biogas from anaerobic
- digestion

→

- Compressed Natural Gas
  Liquefied Natural Gas
- Hydrogen
- Methanol
- Dimethyl Ether
- Fischer-Tropsch Diesel
- Fischer-Tropsch Jet Fuel

- **Cellulosic Biomass**
  - Switchgrass
  - Fast Growing Trees
  - Crop Residues

→

- Ethanol
- Hydrogen
- Methanol
- Dimethyl Ether
- Fischer-Tropsch Diesel
- Fischer-Tropsch Jet Fuel

- Residual Oil
- Coal
- Natural Gas
- Biomass
- Other Renewables (hydro, wind, solar, geothermal)

→

- Electricity

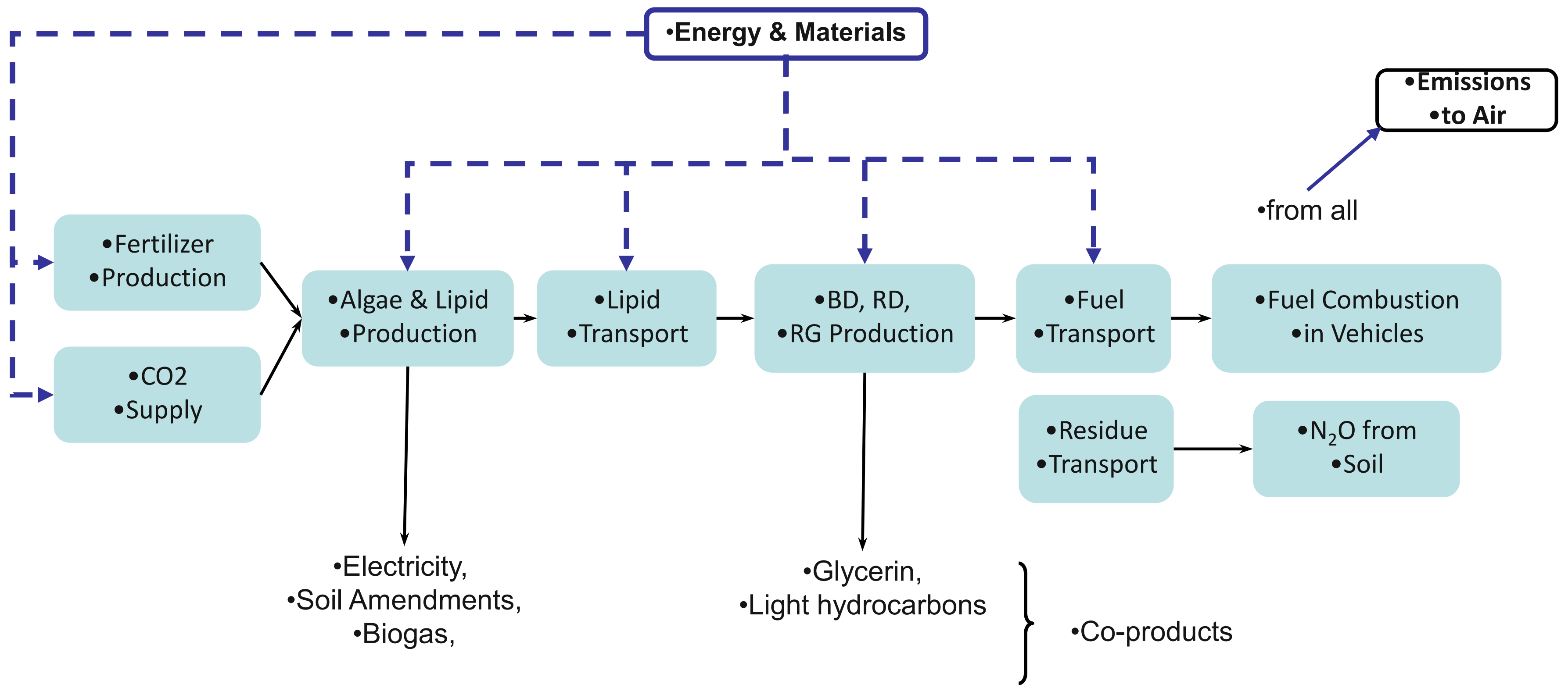
- Algae

→

- Biodiesel
- Renewable Diesel
- Renewable Gasoline
- Renewable Jet Fuel

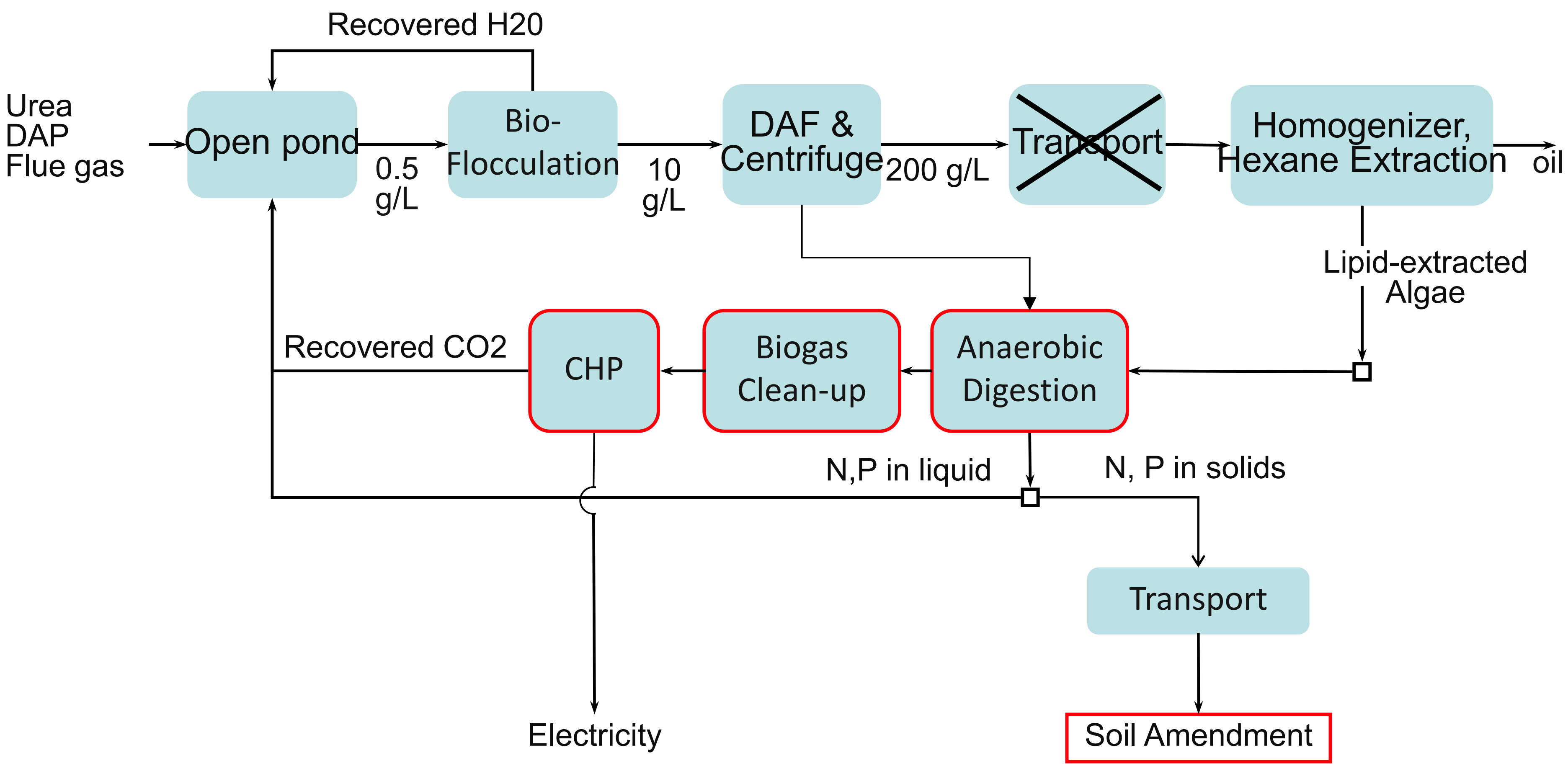
•The yellow boxes contain the names of the feedstocks and the red boxes contain the names of the fuels that can be produced from each of those feedstocks.

Algae System Boundary: Scope Comparable to Petroleum scope

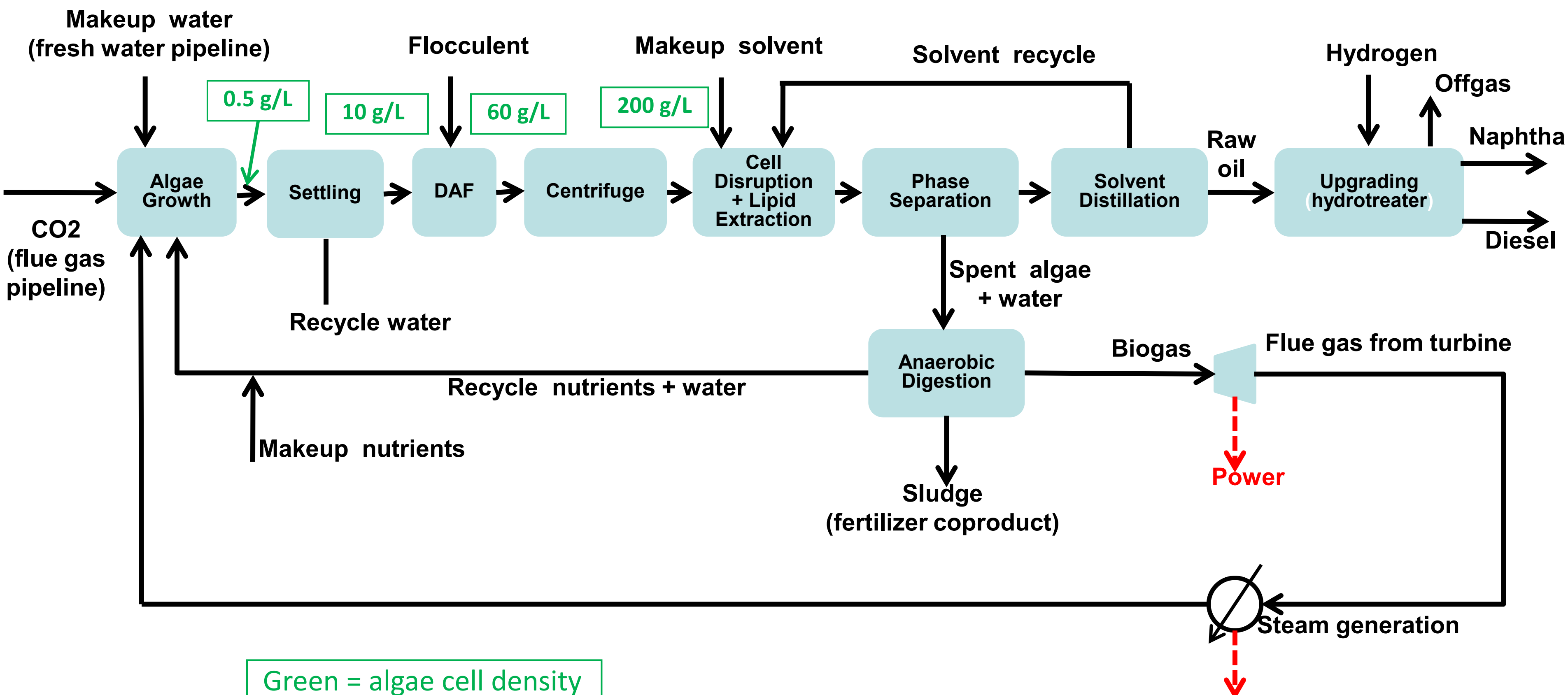


- ➢ Current LCA considers open pond systems
- ➢ System boundary in reports to date excludes infrastructure materials & land-use change

Technical Report and ERL Paper Baseline Scenario (Biodiesel)

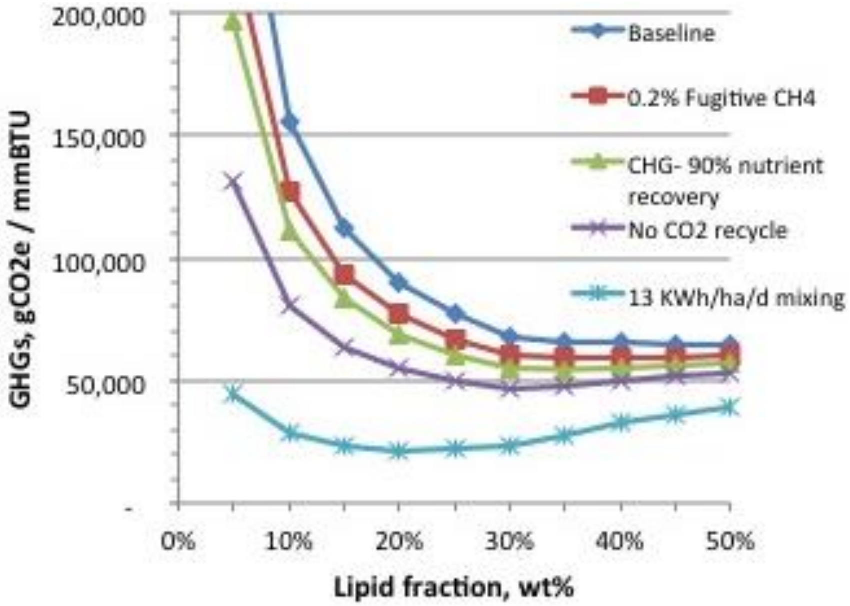


Harmonization Scenario (Renewable Diesel)

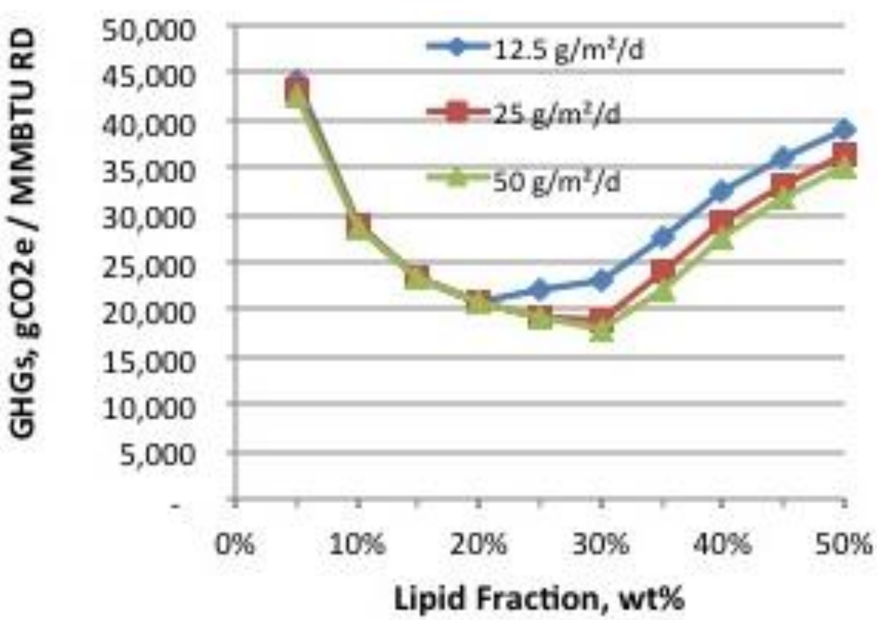


Green = algae cell density

Alternative Harmonization Scenarios were Considered



- Four alternatives at 12.5 g/m^2/d
  - Baseline model had 2.0% fugitive emissions and 45 KWh/ha/d mixing



- "More" isn't always better
  - Non-lipid biomass used for power generation on site. If insufficient, then power comes from the grid, harming GHG results.

Harmonized Mass & Energy Balances and Unit Op. Energy Use

This is a subset of the model parameters. Values were determined from the older literature (Benemann, Oswald, Weissman, ASP) as well as from recent sources recent original analysis, and vendor interviews).

Metric	Before Harmonization		After Harmonization	
	LCA	TEA	LCA	TEA
Productivity, $g/m^2/d$	25	25	per site from RA	
Water demand	0.6 cm/d	0.3 cm/d	per site from RA	
Lipid fraction, wt%	25%	25%	25%	25%
Net harvesting efficiency	85.5%	99%	95%	95%
Net extraction efficiency	85.5%	85.5%	85.5%	85.5%
RD yield from raw oil, wt%	85%	78%	85%	78%
Nitrogen recovery to culture, net	0.76	0.75	0.76	0.76
P recovery to culture, net	0.5	0.5	0.5	0.5
Net N demand, mg/g-algae	14	32	19.5	20.0
Net P demand, mg/g-algae	6.3	6.4	4.1	4.1
Pond mixing, KWh/ha/d	48	48	48	48
Recycle pump, KWh/L	4.80E-05	1.95E-05	2.5E-05	2.5E-05
Water pump from off-site, KWh/L	4.80E-05	3.00E-04	1.23E-04	1.23E-04
DAF, output solids content	10 wt%	10 wt%	6 wt%	6 wt%
Centrifuge power, KWh/g-out	5.77E-05	1.01E-05	1.93E-05	1.94E-05
Homogenizer power, KWh/g-homogenized	2.04E-04	1.10E-04	2.04E-04	2.03E-04
Solvent extraction heat, KWh/kg-oil	1.38	4.48	3.09	3.15
Solvent extraction electricity, KWh/kg-oil	0.54	0.05	0.069	0.069
AD heat demand, KWh/kg-TS	0.54	NA	0.22	0.22
AD electricity demand, KWh/kg-TS	0.136	0.027	0.085	0.085
AD yield, L-CH4/g-TS	0.3	0.333	0.3	0.3
Gross electricity demand (including all CO_2), KWh/kg-oil	5.7	3.7	5.1	4.9
Net electricity imported, KWh/kg-oil	1.4	-1.8	1.32	1.16

Summary of HTL Study Parameters- MITI Paper

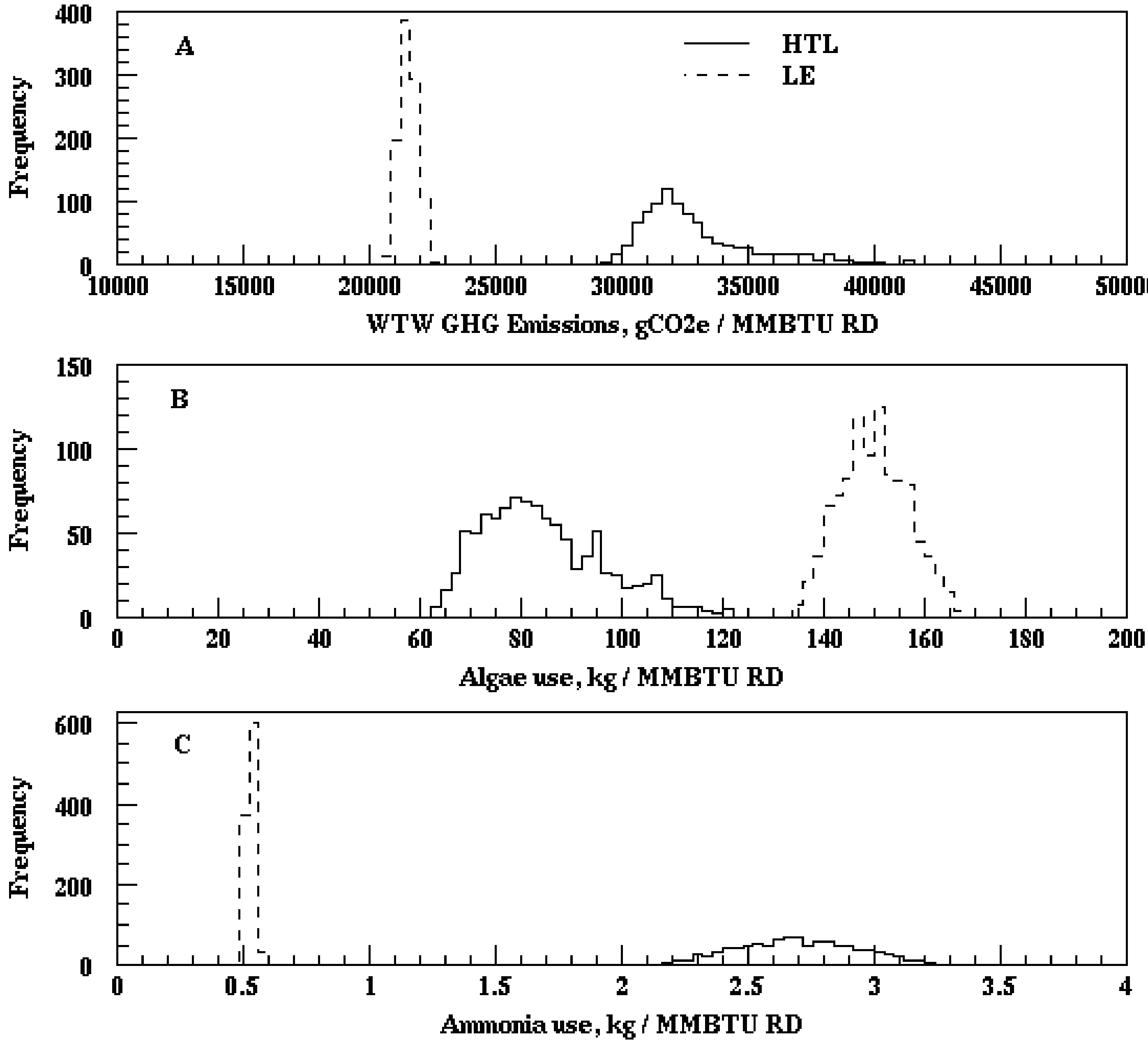
Parameter	Nominal	Low	High
Hydrogen demand, gH/gRD [a]	0.070	0.065	0.075
RD yield, g RD/g HTL oil [a]	0.80	0.75	0.85
HTL oil yield, g/g afdw algae	0.38	0.25	0.51
Reaction temperature, °C	300	250	350
Pump efficiency	50%	25%	75%
Slurry solids (afdw), wt%	15%	10%	20%
HX effectiveness	85%	75%	95%
Nitrogen, wt% in oil	5.7	4.4	7.0
Phosphorus loss, %	15%	0%	30%

[a] LE values are in Table 7

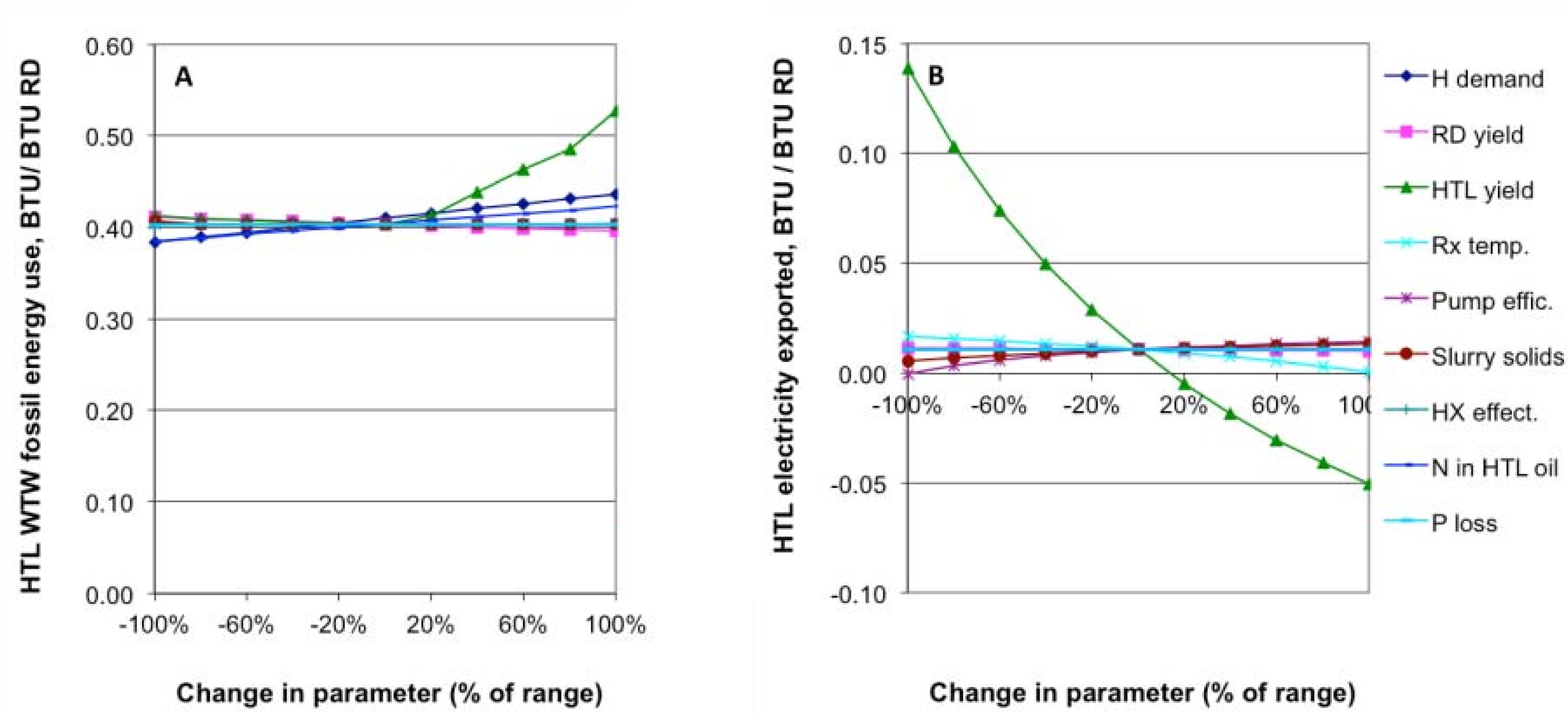
- LE oil upgrading:
  - H demand = 0.040 g H / g RD
  - RD yield = 0.79 g RD / g HTL oil

Monte Carlo Study of Key HTL Parameters

LE = Lipid extraction



HTL Sensitivity Analysis – MITI Paper



- Heat integration mitigates / hides sensitivity to thermal variables
- HTL oil yield, H demand, and N content of oil most significant params
- Non-linearity in HTL oil yield response is the result of electricity balance
  - High HTL yield ⇒ lower energy in aqueous ⇒ reduced co-power

Results for Nominal Parameter Values

	Direct energy use (BTU / BTU RD)			
	HTL		LE	
Operation on site	Electricity	Heat	Electricity	Heat
CO_2 delivery	0.021	0.00	0.033	0.00
Growth & 1st dewatering	0.090	0.00	0.16	0.00
2nd dewatering	0.047	0.00	0.085	0.00
Oil production	0.025	0.18	0.10	0.32
CHG	0.00 [a]	0.00 [a]	0.11	0.18
Biogas cleanup	0.019	0.00	0.065	0.00
Total	0.20	0.18	0.55	0.50
Electricity recycled	-0.20		-0.55	
Heat recycled		-0.18		-0.50
Electricity exported	0.011		0.017	

	Material consumption (kg / MMBTU RD [b])	
	HTL	LE
Algae	83	150
Ammonia [c]	2.7	0.52
Diammonium phosphate [c]	0.67	0.45

	RD production (BTU / BTU RD)	
	HTL	LE
Total direct energy [d]	0.085	0.049

[a] Since CHG is integrated with HTL, it is included in the oil production step
[b] 24 kg RD / MMBTU
[c] Net, after nutrient recovery from CHP
[d] Includes hydrogen for hydroprocessing expressed as BTU by its lower heating value

Nitrogen Balance in the MITI Paper

- Nitrogen in the feedstock goes either to the produced oil or to other fractions
  - HTL oil 5.7 wt% N (Average value from literature)
- Balance of feedstock N recovered as ammonia from CHG step
  - This portion of the N was recycled to the pond with assumed 5% loss to volatilization
- N in oil assumed to be lost during remote hydrotreatment
  - See discussion in MITI paper with regard to options at the refinery.
  - http://greet.es.anl.gov/publication-hydro-lipid-comparaison
- Net result
  - 64% of N is recycled via liquid phases from thermal processing on site
  - 37% of N is lost via incorporation of N into oil which is later removed during off-site hydrotreatment

Responses to Previous Review Comments

- *Baseline scenarios near completion, but value of project is for evaluation of other scenarios*
  - Since the 2011 review, scenarios for biodiesel from extracted lipids, renewable diesel from HTL, combined HTL of residuals and lipid extraction, have been studied in detail including Monte Carlo studies of parameter distributions.
- *There should be an attempt to integrate several of the modeling efforts, and there should be some movement towards defining best practices*
  - LCA, TEA, and resource assessment were integrated and a detailed, multi-lab technical report was prepared. Key questions for LCA, TEA, and RA were defined to elucidate best practices for algae modeling in these modeling domains.

Responses to Previous Review Comments

- *Although a good approach, much of the assumptions and process pathway is rather devoid of reality described in Benneman and co-author's reports. More contact with the consortiums and groups would be helpful.*
  - Actually, many of the seminal reports were used extensively in preparation of the models. A long standing relationship with Dr. Benemann prior to the 2011 review and continuing after has been valuable as has relationships with Dr. Lundquist and other researchers. We established a long term collaboration with NAABB and have played important roles in the NAABB analysis effort. Benemann described our technical report as “Best LCA analysis available” in his work, “Life Cycle Analysis for Microalgae Oil Production” (Benemann, Woertz, Lundquist, *Disruptive Science and Technology,* **1**(2) 68-78, 2012).

Publications

- Frank, E.D., J. Han, I. Palou-Rivera, A. Elgowainy, and M.Q. Wang, 2011, *Life-Cycle Analysis of Algal Lipid Fuels with the GREET Model*, Center for Transportation Research, Argonne National Laboratory, ANL/ESD/11-5

- Frank, E.D., J. Han, I. Palou-Rivera, A. Elgowainy, and M.Q. Wang, 2012, “Methane and nitrous oxide emissions affect the life-cycle analysis of algal biofuels”, *Environmental Research Letters:* ***7****(1) 014030*

- Frank, E. D., A. Elgowainy, et al., 2012, "Life cycle comparison of hydrothermal liquefaction and lipid extraction pathways to renewable diesel from algae." *Mitigation and Adaptation Strategies for Global Change*: 1-22.

- Davis, R., D. Fishman, E.D. Frank, M.S. Wigmosta, A. Aden, A.M. Coleman, P.T. Pienkos, R.J. Skaggs, E.R. Venteris, M.Q. Wang, 2012, Renewable Diesel from Algae Lipids: An Integrated baseline for Cost, Emissions, and Resource Potential from a Harmonized Model, ANL, NREL, and PNNL

Publications (cont'd)

- C. Canter, M. Urgun-Demirtas, and E.D. Frank, 2013, "Infrastructure associated emissions for renewable diesel production from microalgae." In preparation for submission to *Algal Research*

- Z. Wang, M. Urgun-Demirtas, C. Canter, R. Davis, and E.D. Frank, 2013, "Fugitive methane emissions from anaerobic digestion of lipid extracted algae." Submitted to *Environmental Science and Technology*

- M.C. Johnson and E.D. Frank, 2013, "Energy consumption during the manufacture of nutrients for algae cultivation." Submitted to *Algal Research*

Selected Presentations

- Johnson, M.C., Waller, P.M., Zhu, Y., Frank, E.D. (2013) “Life Cycle Analysis of Algal Biofuels: Implications of NAABB R&D.” Accepted for oral presentation at 3rd International Conference on Algal Biomass, Biofuels, & Bioproducts, June 16-19, 2013
- Frank, E., Elgowainy, A., Han, J., Wang, M. (2012) “Integrated Algal Biofuel Baseline Analysis: Emissions and Energy Consumption from a Harmonized Model.” (2012) Algae Biomass Summit, September 24-27, 2012.
- Frank, E., Han, J., Palau-Rivera, I., Elgowainy, A., Wang, Z., Wang, M. (2012) “Life-cycle Analysis of algal fuels with GREET: Results and Updates.” 2nd International Conference on Algal Biomass, Biofuels, & Bioproducts, June 10-13, 2012.
- Frank, E., Wang, M. (2012), “Algal Biofuels Modeling: Planning for a Viable Industry.” World Renewable Energy Forum, May 14, 2012.
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Selected Presentations

- Frank, E., Wang, M., Han, J., Elgowainy, A., Palou-Rivera, I. (2011), "Life Cycle Analysis of Algal Biofuels with GREET." Society for Biological Engineering Conference on Electrofuels Research, November 6-9, 2011
- Frank, E., Wang, M., Han, J., Elgowainy, A., Palou-Rivera, I. (2011), "Life Cycle Analysis of Algal Biofuels with GREET." Illinois Sustainability Technology Center Seminar Series on Sustainability, Urbana-Champaign, November 2, 2011
- Frank, E., Wang, M., Han, J., Elgowainy, A., Palou-Rivera, I. (2011), "Life Cycle Analysis of Algal Biofuels with GREET." ABO Algae Biomass Summit, October 25-27, 2011
- Dunn, J., E., Wang, M., Han, J., Elgowainy, A., Palou-Rivera, I. (2011), "Life Cycle Analysis of Algal Biofuels with the GREET Model." The Second Annual U.S.-China Advanced Biofuels Forum, September 16, 2011 (Presented by J. Dunn)
- Frank, E., Wang, M., Han, J., Elgowainy, A., Palou-Rivera, I. (2011), "Life Cycle Analysis of Algal Biofuels with the GREET Model." APEC Workshop on the Resource Potential of Algae for Sustainable Production of Biofuels in the Asia Pacific Region, September 12, 2011 (Presented by M. Wang)
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Selected Presentations

- Frank, E., Wang, M., Han, J., Elgowainy, A., Palou-Rivera, I. (2011), "Life Cycle Analysis of Algae-Based Fuels with the GREET Model." NRC Committee on the Sustainable Development of Algal Biofuels, June 13, 2011
- Frank, E., Wang, M., Han, J., Elgowainy, A., Palou-Rivera, I. (2011), "Life Cycle Assessment Tools for Algal Biofuels." AICheE Spring Meeting, March 13-17 2011, Chicago
- Frank, E. (2011), "A Model of CO2-Fed Algal Biofuel Potential in the US." AICheE Spring Meeting, March 13-17 2011, Chicago