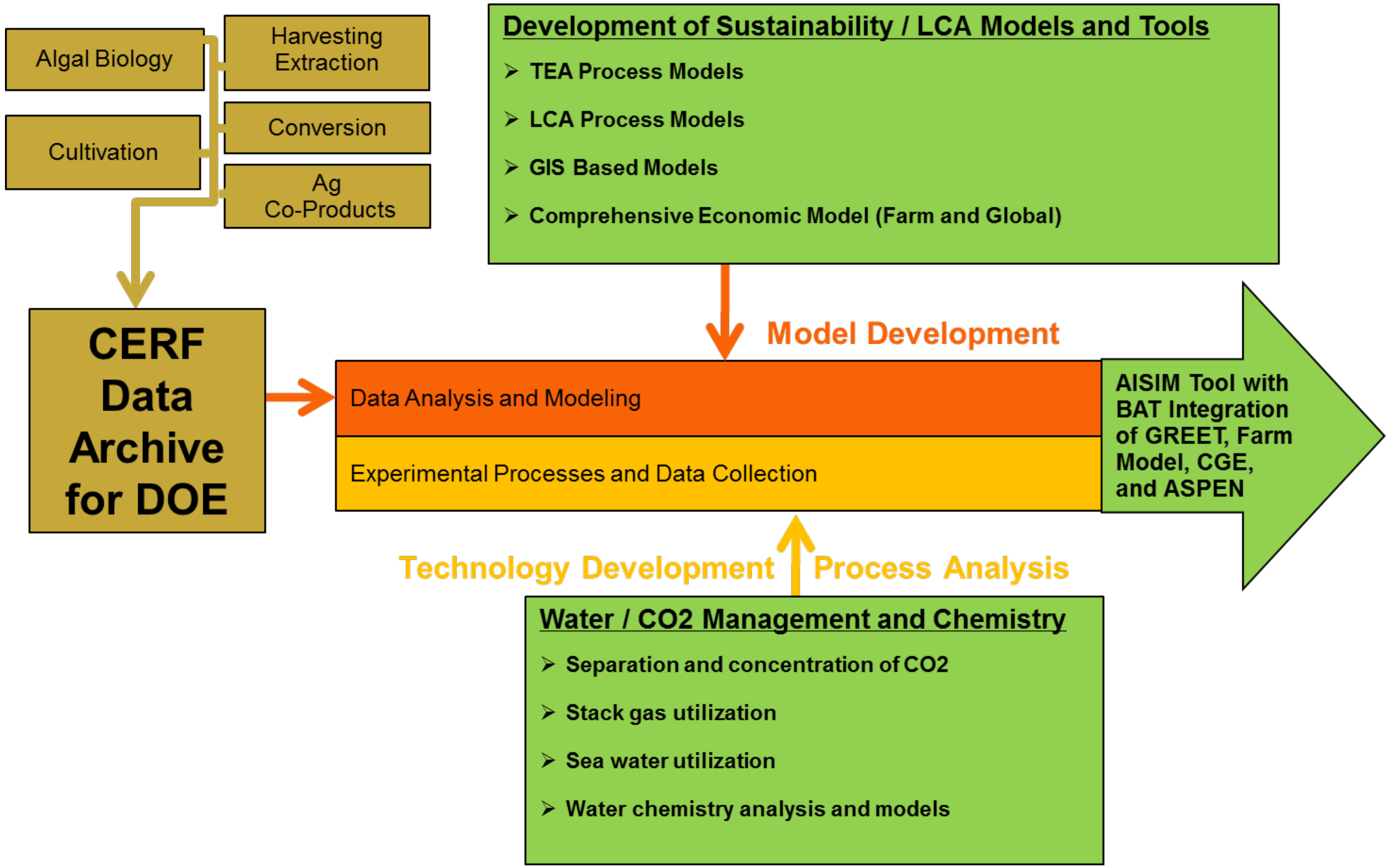
National Alliance For Advanced Biofuels and Bio-products

Sustainability Technical Accomplishments, Progress and Results

Presented by James Richardson, NAABB Sustainability Team Co-Leader

Sustainability Task Framework



AISIM = NAABB Algae Integrated Simulation System

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Model	Description	Lab
BAT	Biomass Assessment Tool	PNNL
GREET	Greenhouse gases, Regulated Emissions, and Energy Use in Transportation	ANL
FARM	Farm-level Algal Risk Model	TAMU
APA	Applied Production Analysis	NMSU
CGE	Computable General Equilibrium Global Simulation Model	TAMU
ASPEN	Aspen Tech Modeling Software	Various

Measures of Sustainability Generated by AISIM

- Risk Adjusted Profit
- Prob. of Success
- CAPEX/OPEX
- GHG Emissions
- Net Energy
- Land Use
- Marginal Cost
- Water Use Needs

NAABB AISIM

Experimental Results

AB

1. 2.5x Yield GMO
2. *Chlorella sorokiniana*-1412
3. Temperature-PAR based estimates

CULT

1. 5 g/l achieved in PBR
2. 12 g/m2/day in Open Pond
3. ARID Raceway design specifications

H&E

1. 408,780 L/Hr harvesting
2. Harvesting at 0.04 kWhr/m3
3. 950,000 L/Day Extraction though put

AISIM

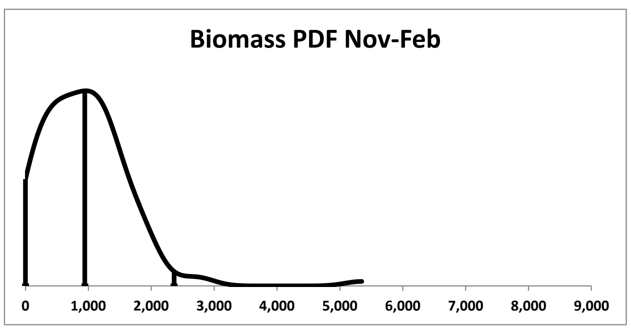
- BAT
- GREET
- FARM
- APA
- CGE

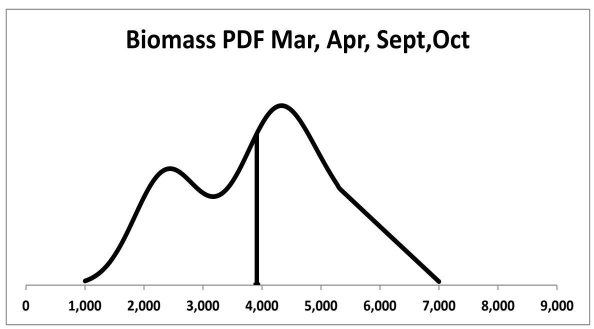
FARM = Farm-level Algal Risk Model

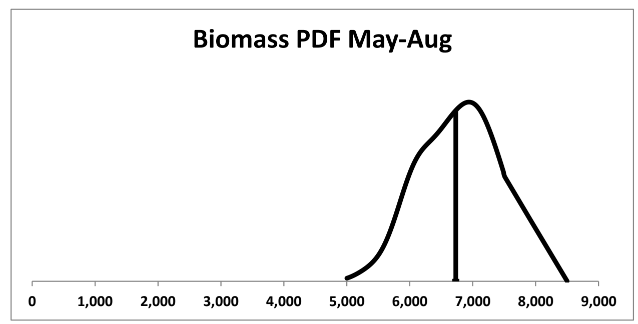
- **FARM was developed for NAABB economic sustainability analyses**
- **FARM is a Monte Carlo model that simulates an algae farm with an assumed debt structure and business plan using alternative technologies for biology, cultivation, harvesting, extraction, and alternative co-products**
- **FARM model harmonized with DOE algae-to-diesel model and found that FARM's costs of production were within $0.05/gallon of the DOE Harmonized model**
- **Following the DOE harmonization report in FY12, FARM was validated against DOE model**
- **FARM's costs of production were very close to DOE's FY12 harmonized cost of production for diesel**
    - DOE $12.15/gal
    - FARM $12.25/gal

BAT (Biomass Assessment Tool)

- **BAT is a GPS based, national-scale resource and production assessment model for producing algal biofuels**
  - Used for DOE Harmonization report in FY12
  - Analyzed 11,000 potential sites for growing algae in the United States
- **Water temperature, evaporative losses, solar radiation, and rainfall estimated from 30 years of hourly meteorological data**
  - Simulated monthly biomass and lipid production and net water requirements for 30 years
- **30 years of monthly biomass and lipid production and net water use defined probability distributions which were used in FARM to simulate BAT's nine best locations**



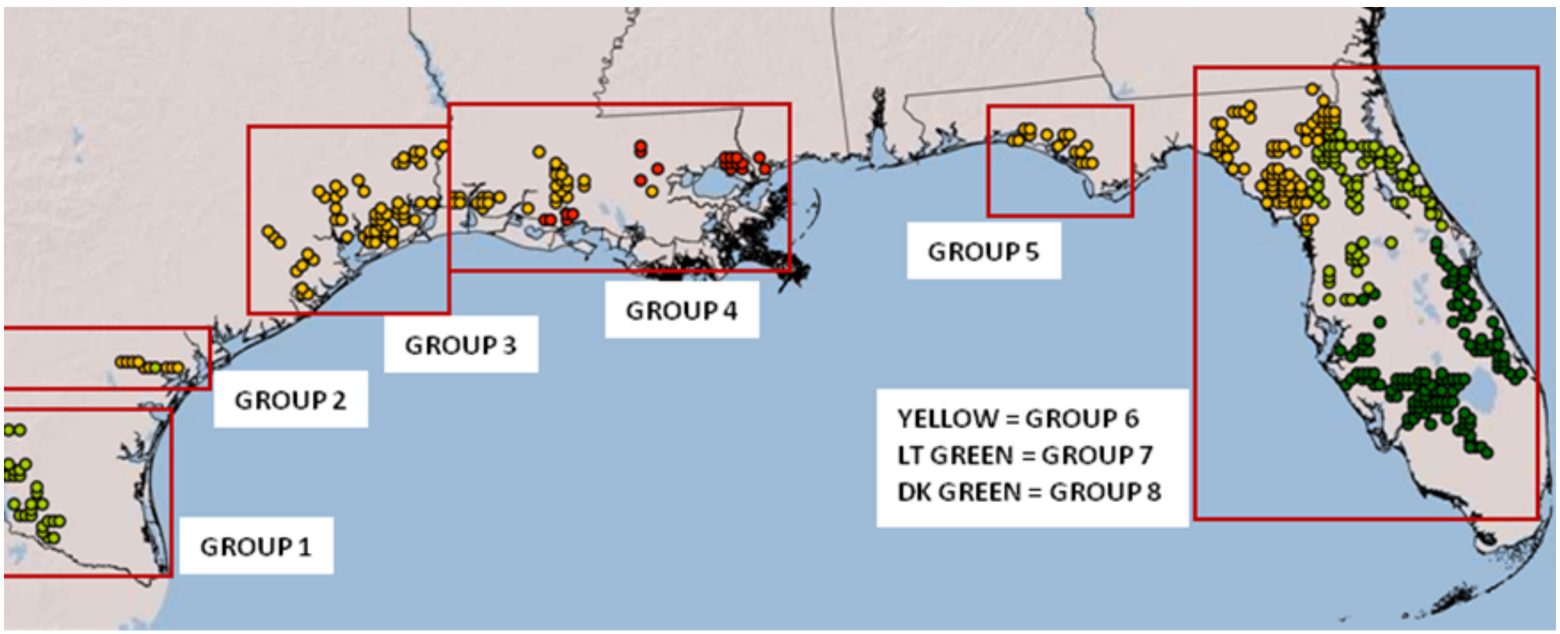




BAT (Biomass Assessment Tool)

- **FARM simulated the cost of production and probability of economic success for the median sites in the 9 best regions in DOE Harmonized FY12 report**

- **Three production scenarios analyzed for 9 sites: Generic Strain, Freshwater Chlorella, Saltwater Salina**

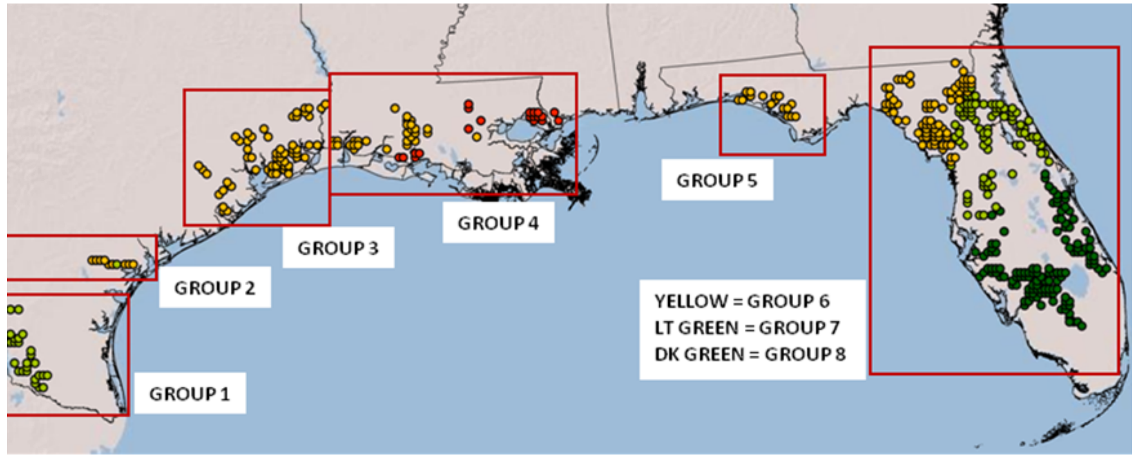


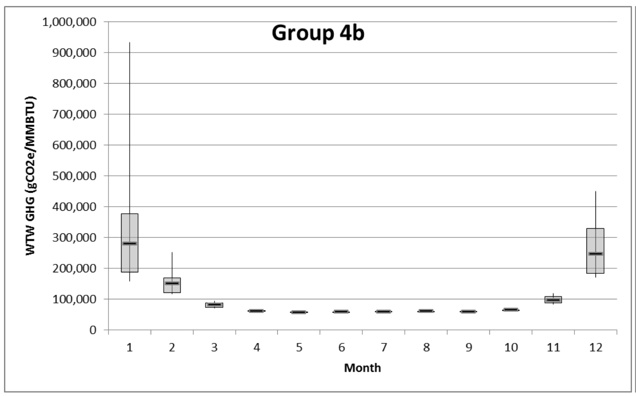
FARM Results for Nine BAT Regions

- Farms in all nine regions resulted in very low probabilities of economic success
- Non-zero probabilities of success in two of the three production scenarios occurred only when CAPEX and OPEX were reduced by 90%
- Most profitable scenarios were: Salina Saltwater, followed by Freshwater Chlorella
- Most profitable regions were: South Florida, Central Florida, Northern Florida and South Texas; with probabilities of success less than 50% even with 90% cuts in CAPEX and OPEX
- Costs per gallon for diesel were \$20-\$21/gallon for the four most profitable regions, after assuming 90% cuts in CAPEX and OPEX

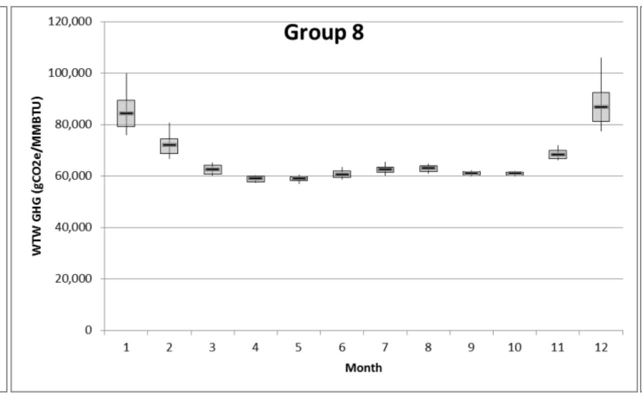
GHGs and Energy Use for Algae with GREET

- **GREET LCA analysis**
  - Study of LCA seasonal variation
  - Simulated 30 years individually
  - Estimated costs of production and biomass production

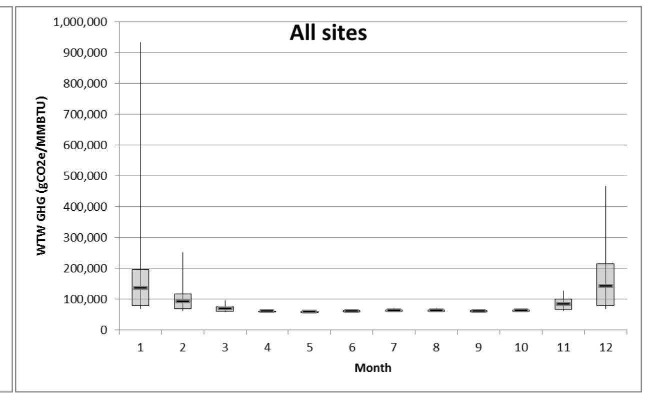




Year to year variation at some sites is large in some months.



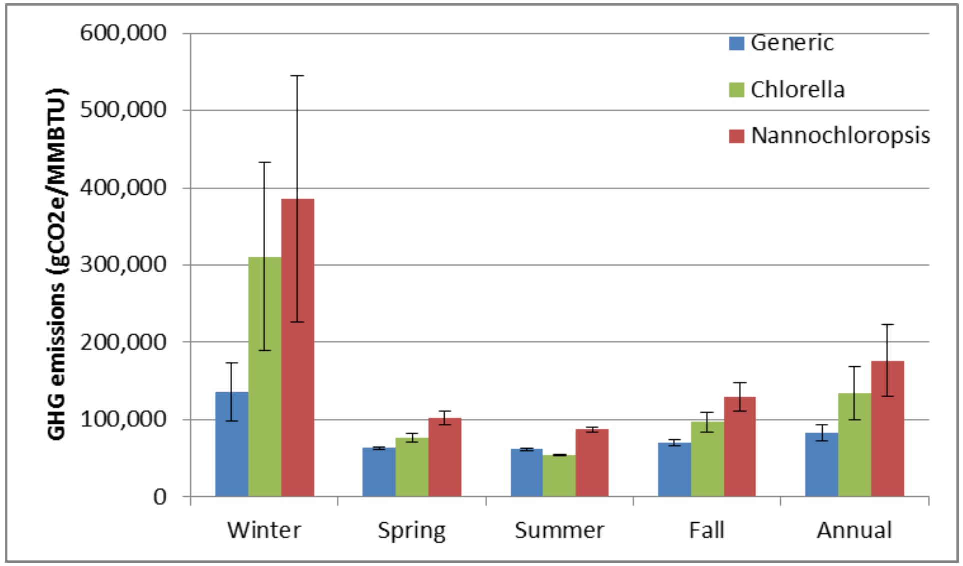
Variation at other sites smaller, but still significant.



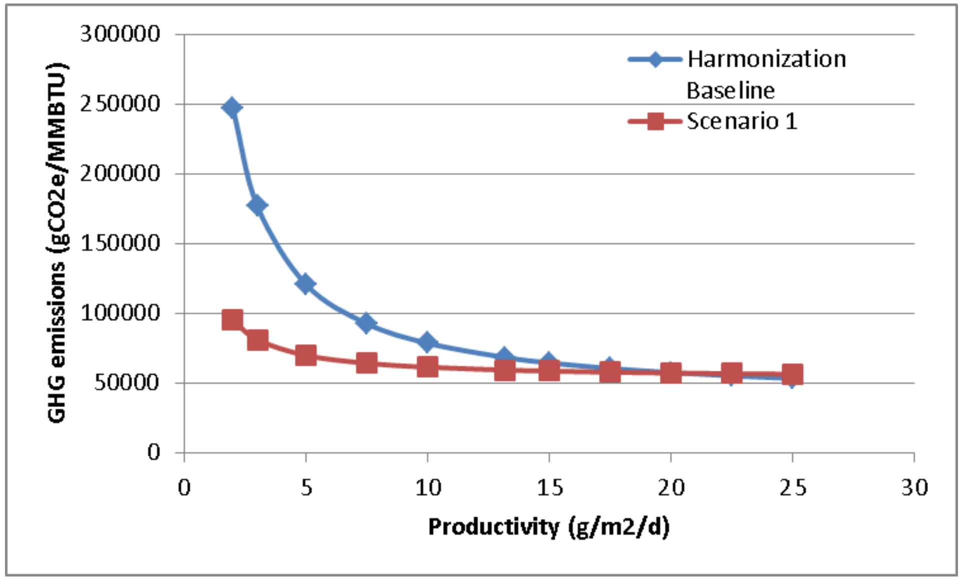
Most sites similar in spring & summer, but many fail in other months.

GHGs and Energy Use for Algae with GREET

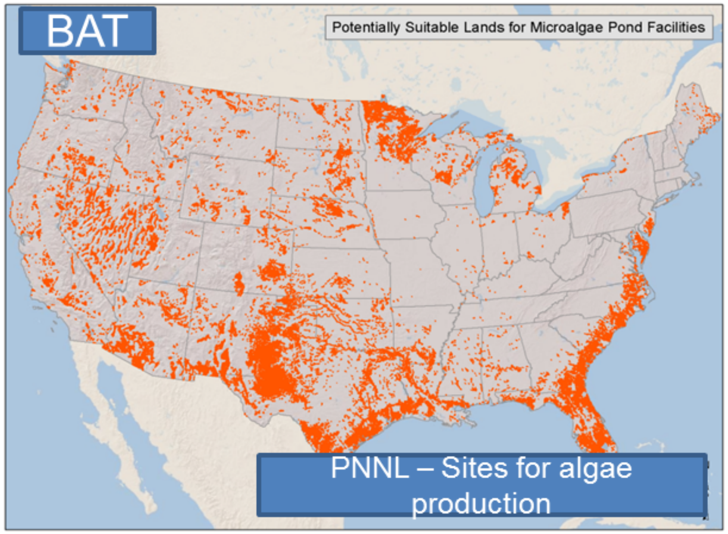
- **BAT analyses using real species performed poorly for GHG emissions compared to theoretical FY12 Harmonization species (“generic”) analyzed with BAT**

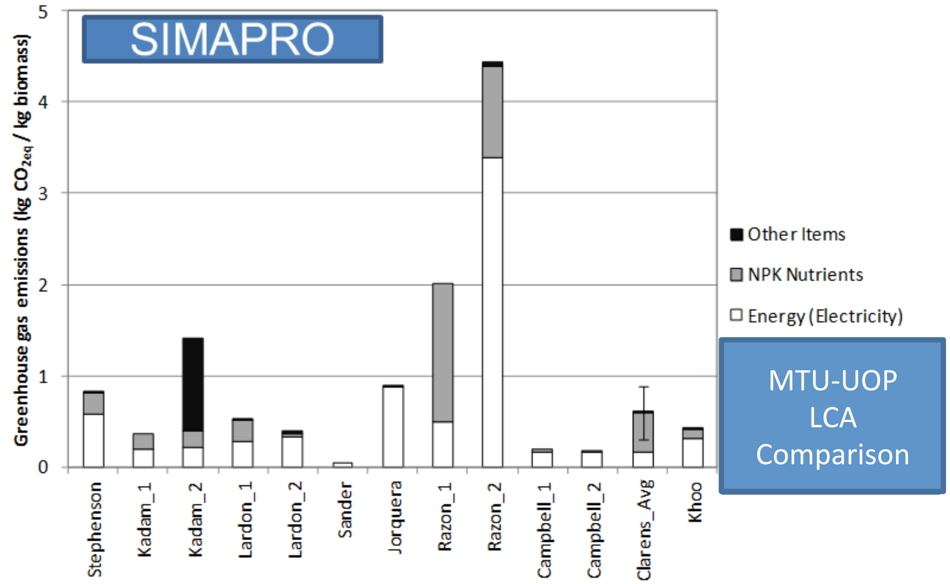


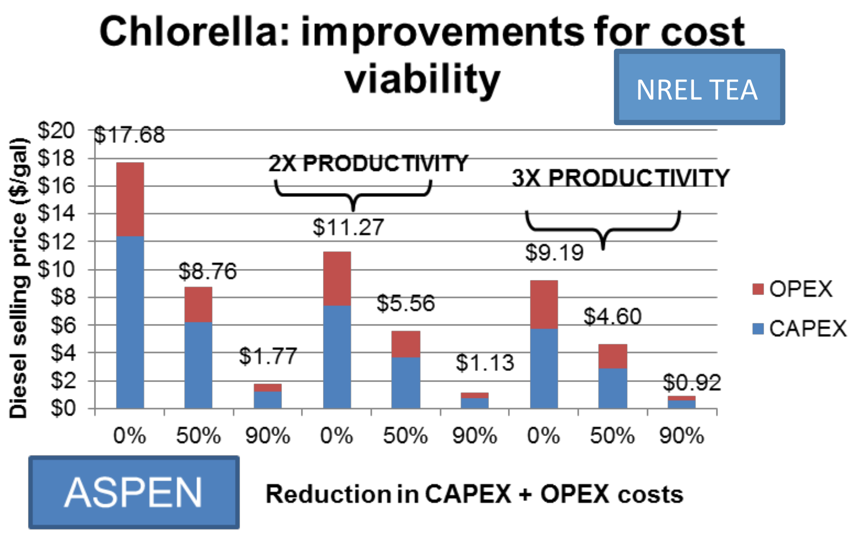
- **Analysis of ARID with GREET**
  - ARID with reduced circulation energy
  - Improved low-productivity GHG behavior
  - Higher productivity asymptote requires improved energy efficiency for harvesting and processing with HTL-CHG

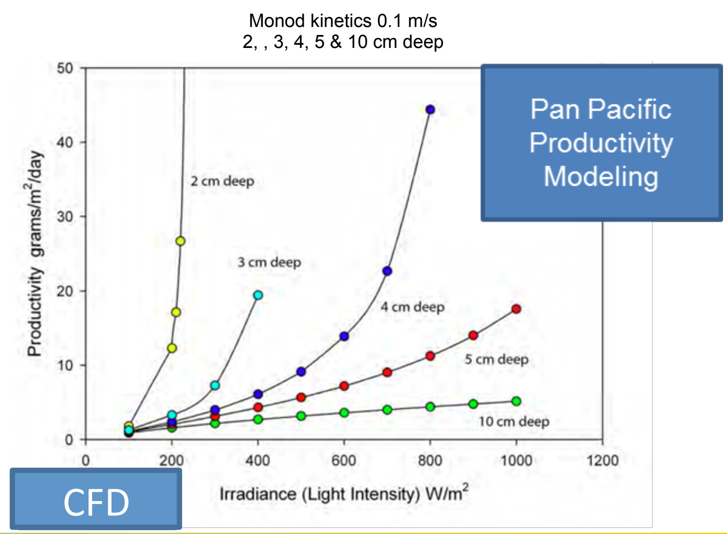


Sustainability/Environmental Modeling Results Developed from Several Partners in NAABB









Modeling and Analysis Efforts

MTU-UA-UOP SIMAPRO vs GREET	Environmental impact of algae cultivation and environmental burden from nutrient, energy, and cultivation inputs	1. GHG 2. Energy Use 3. Land Use Change by Land Type 4. Nutrient Use and Burden
U of PA ASPEN	Conversion of algae extracts to biodiesel using the Albemarle-Catilin conversion process to transesterified biodiesel	1. GHG 2. Energy Use 3. CAPEX/OPEX 4. Profitability Analysis
UA ASPEN and Chemcad	Sustainability of biodiesel from microalgae. Nutrient sustainability, environmental burden from cultivation, and impact of H&E. Pond liner impacts.	1. GHG 2. Energy Use 3. Nutrient Use 4. Eval of 6 different NAABB H&E Tech.

Modeling and Analysis Efforts

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NREL ASPEN	Techno-Economic Analysis extending DOE Baseline with select NAABB technology process steps. Focused on seasonal variation	1. CAPEX/OPEX 2. Profitability Analysis 3. Profitability with changed processes
Pan Pacific ASPEN	Comprehensive TEA, LCA, and Computation Fluid Dynamic modeling of flow in ponds and optimization of process steps. Best case scenario for algae fuel	1. GHG and Energy Use 2. Computational Fluid Dynamics 3. CAPEX/OPEX and Profit 4. Process Optimization, Optimal product
PNNL ASPEN	Predictions of cost, output, and waste streams using HTL , Gasification and conversion technology	1. GHG 2. Energy Use 3. CAPEX/OPEX 4. Profitability Analysis

Modeling and Analysis Efforts

- **Process models including:**
  - Transesterification (UPenn)
  - Growth and harvesting (NREL and Pan Pacific)
  - Detailed thermodynamic-based end-to-end model (Pan Pacific)

- **Sustainability and economic models were developed for a complex array of scenarios, technologies, and process steps**
  - Models include Life Cycle Assessment, Life Cycle Inventory, and Monte Carlo evaluation of profitability

- **DOE will be receiving 500 pages of new LCA results and model analyses**

- **Examples:**

- (1) Handler, et al. 2012. "Evaluation of environmental impacts from microalgae cultivation in open-air raceway ponds: Analysis of the prior literature and investigation of wide variance in predicted impacts." Algal Research. 1(2012) 83-92.

- (2) Silva, C. S., L. A. Fabiano, G. Cameron, and W. D. Seider, "Optimal Design of an Algae Oil Transesterification Process," in Karimi, I. A., and R. Srinivasan (Ed.), Proceedings of the 11th Int'l. Symp. on Proc. Sys. Eng., Singapore, 15-19 July 2012.

- (3) Dunlop, E., A. K. Coldrake, C. S. Silva, and W. D. Seider, "An Energy-limited Model of Algal Biofuel Production: Towards the Next Generation of Advanced Biofuels," *AIChE J.*, submitted.

Modeling and Analysis Critical Factors

- **Barriers to improved modeling are**
  - Consistent data collection procedures and standards
  - Collection of consistent variables across different procedures, processes, labs and facilities
  - Scale too small to be meaningful for results on TEA/LCA
  - Little information on how lab scale experiments can be scaled up to meaningful size
  - Inadequate information on economies of scale
  - Inadequate information on process conditions and documentation of procedures, measurements, and variables

- **Key to better models will be**
  - Better Data
  - Experiments planned around the data and sufficient scale to be meaningful

Cultivation Data

- New data set contains more than 3,500 observations on cultivation parameters, sites in Pecos, TX, Las Cruces, NM, and Tucson, AZ
- Four years of data on temperature, PAR, precipitation, media mix, water use and re-use, productivity, optical density, salinity, and lipid characterization provided for three sites
- Empirically estimated productivity and input factors
- Provide a field-scale estimate of productivity across seasons and locations using more than 50,000 liters of water
- Includes a variety of media use and recycle regimes as well as water chemistry and weather impacts on production
- Descriptive statistics and dataset will be made available to researchers

Cultivation Data Modeling

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- **Preliminary estimates from the Pecos data show significant variation across seasons for the same strains**
  - Estimated average AFDW g/m2/day for June was 12.56 +/- 4.58 (μ,σ^2)
  - September production of biomass declines to a mean of 2.60 +/- 10.93 (μ,σ^2)
- **Shorter days and cooler temperatures in September and increasing differential between night time high and low are expected to explain the difference**
- **Cultivation data is being used to develop an Applied Production Analysis (APA) to predict average annual production based on outdoor cultivation in raceway ponds**
- **APA biomass yield projections can be fed into FARM**
- **Using econometric methods to predict productivity data from the time series cultivation generated by NAABB projects**

Value of Co-products for NAABB

- **Econometric analyses of value for lipid extracted algae (LEA) for animal and mariculture feed, and fertilizer**

- **Considered the chemical composition of LEA and whole algae, in particular:**
  - Energy
  - Fat
  - Protein
  - Micronutrients
  - Amino acids

- **Estimated the value of LEA based on historical values the feed ingredient market has placed on these nutritional attributes and the 2013 projected prices for feed ingredients for ruminants and mariculture**

Value of LEA as a Soil Amendment

- **Assuming an LEA average chemical makeup of:**
  - Nitrogen 3.25%
  - Phosphorus 0.49%
  - Potassium 0.65%
  - Carbon 31.4%

- **Current prices for N, P, K, and Char the value of LEA is about $30/ ton**

Value of LEA for Animal Feed

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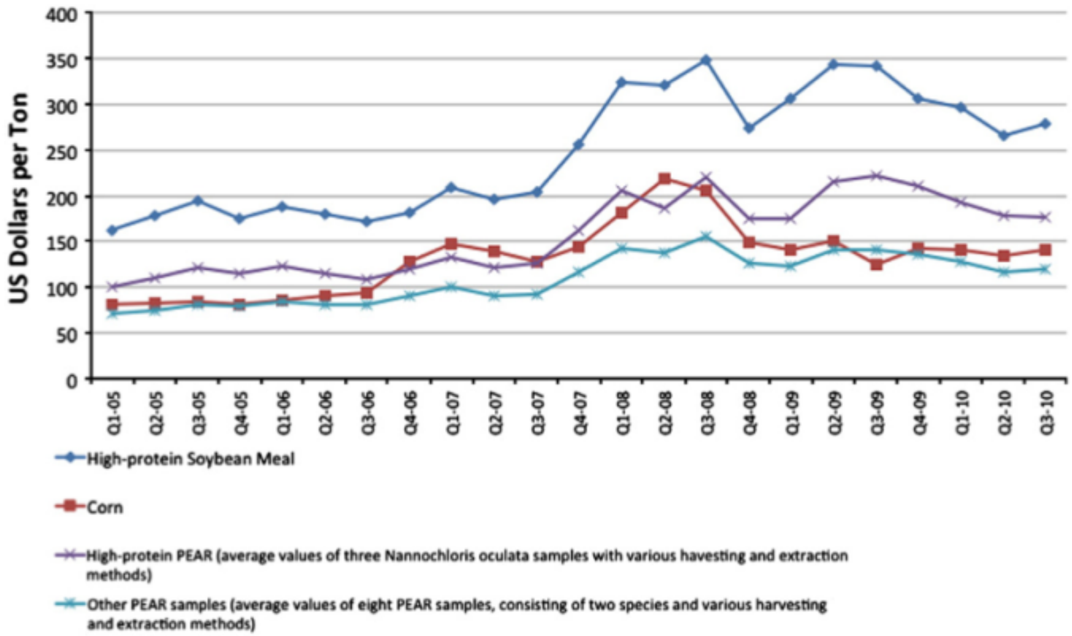
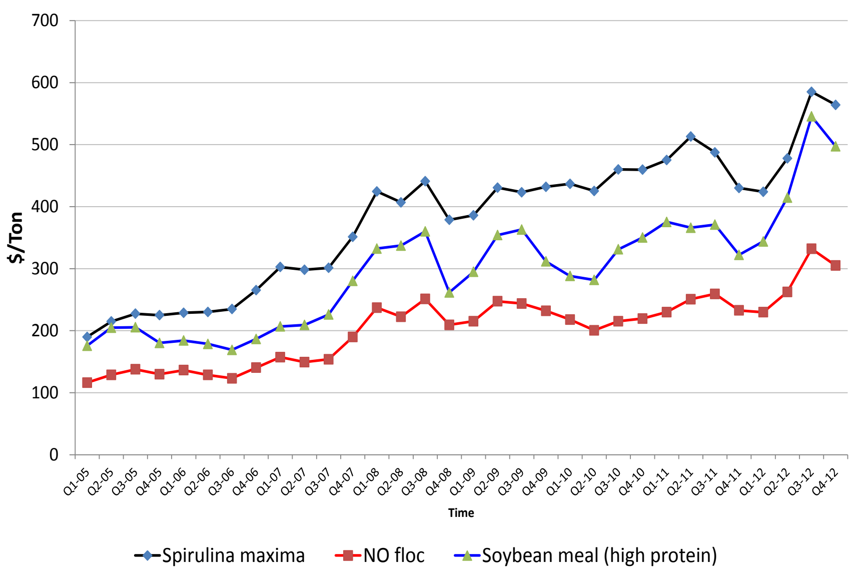
- **Hedonic econometric models developed to estimate intrinsic value of LEA based on fractions of energy, protein, fat, etc. in LEA**

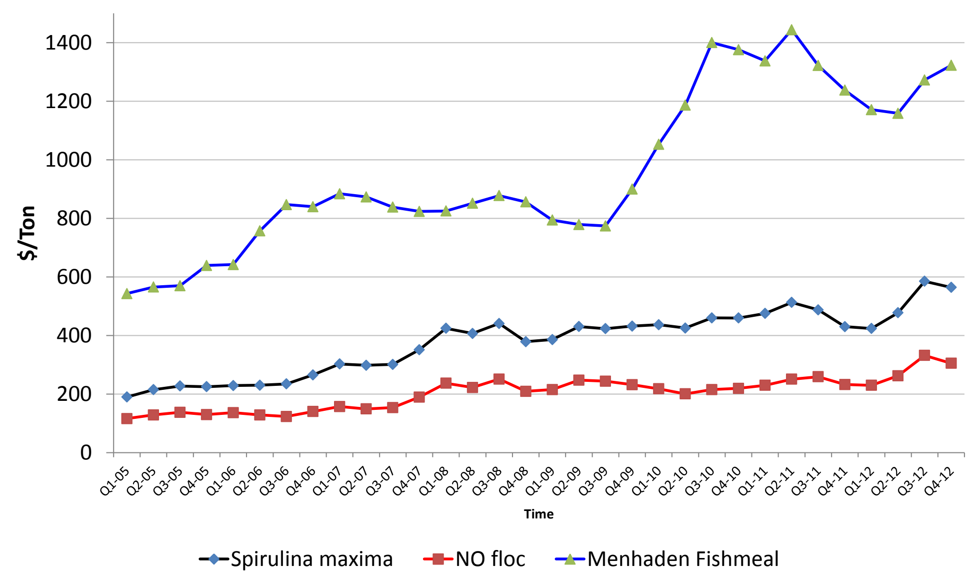
- **LEA intrinsic market value is $100 to $160 per ton less than soybean meal – $130-$190/ton in 2013**
  - Depending on specie, harvesting, and extraction
  - Valued higher the more oil residue remains
  - Must be of consistent quality and assay for livestock industry to adopt



Value of LEA for Shrimp and Fish Feed

- **Based on fractions of energy, protein, fat, etc. in LEA and whole algae; the value of these ingredient in mariculture rations are:**
  - Whole algae averages $82/ton more than soybean meal – about $373/ton in 2013
  - LEA averages $94/ton less than soybean meal – about $200/ton in 2013
  - A non-market advantage of feeding LEA to mariculture is it replaces a portion of fishmeal in the ration thus protecting the ocean's fish population





Global Economic Analysis for NAABB

- **Developed a global computable general equilibrium (CGE) model of the world economy with biofuels sector and algae biofuels component**
- **Including trade in crude oil, land use change, and the effects on global food insecurity**
- **Model used to analyze the equilibrium effects of a 5bgy algal biofuels industry on energy, food, and agricultural markets**
- **Results show that by meeting 6.5 billion gallons of ethanol equivalent for the RFS2 mandate in 2030 with 5 bgy of algae biodiesel will reduce the number of food insecure people in the World relative to meeting this same level of production using grain base ethanol**
  - Also decreases U.S. oil dependency and reduces crude oil prices
  - Details in the NAABB final report

Summary of Sustainability Outcomes

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Completed Models

- 6 Independent Life Cycle Analyses
- GREET Analysis of NAABB Data
- Detailed Microeconomic Analyses of Algae Fuels and Value of LEA
- Detailed Macroeconomic Analysis of Algae Fuels
- Updated Resource Assessment Tool
- Comprehensive Cultivation, Characterization and Water Data Set on Algae
- Optimized Process Scenarios

Key Results

- 40% reduction in media cost
- 1.7 x increase in demonstrated productivity (from 7 g/m2/day to 12 g/m2/day)
- Predicted decrease in cost of fuel from $12 gallon to $5.00-$7.00/gallon
- ARID shows promise to mitigate poor cool season performance
- HTL-CHG shows promise of increased fuel yield by LEA processing
- Predictions of algae biomass by location for more than 11,000 sites in the US

Sustainability Milestones and Deliverables

Milestones (M), Decision Points (GN) and Deliverables (DL)	Time (mo) Status
F.1.DL.1: ASPEN process model for producing synthetic natural gas, liquid algal biofuel and chemical feedstock completed. (report)	12 Complete
F.DL.1: AISIMS data integration and standardization framework established. (report)	24 Complete
F.ML.1: Web based AISIMS modeling and database system fully implemented. (report)	36 Complete

- **Six ASPEN models developed for alternative situations and paradigms**
  - Delivered to DOE and research community
- **AISIM data integration and standardization**
  - Experimental results from NAABB partners used in sustainability models – ASPEN, LCA, and FARM
  - Cultivation data base delivered to research community and integrated in FARM
  - BAT model results integrated into LCA study and FARM
- **AISIM modeling system fully integrated**
  - FARM developed, harmonized, tested and allied to scenario analyses for farm sustainability

Questions Before the Scenario Analyses?

Sustainability Scenario Analysis

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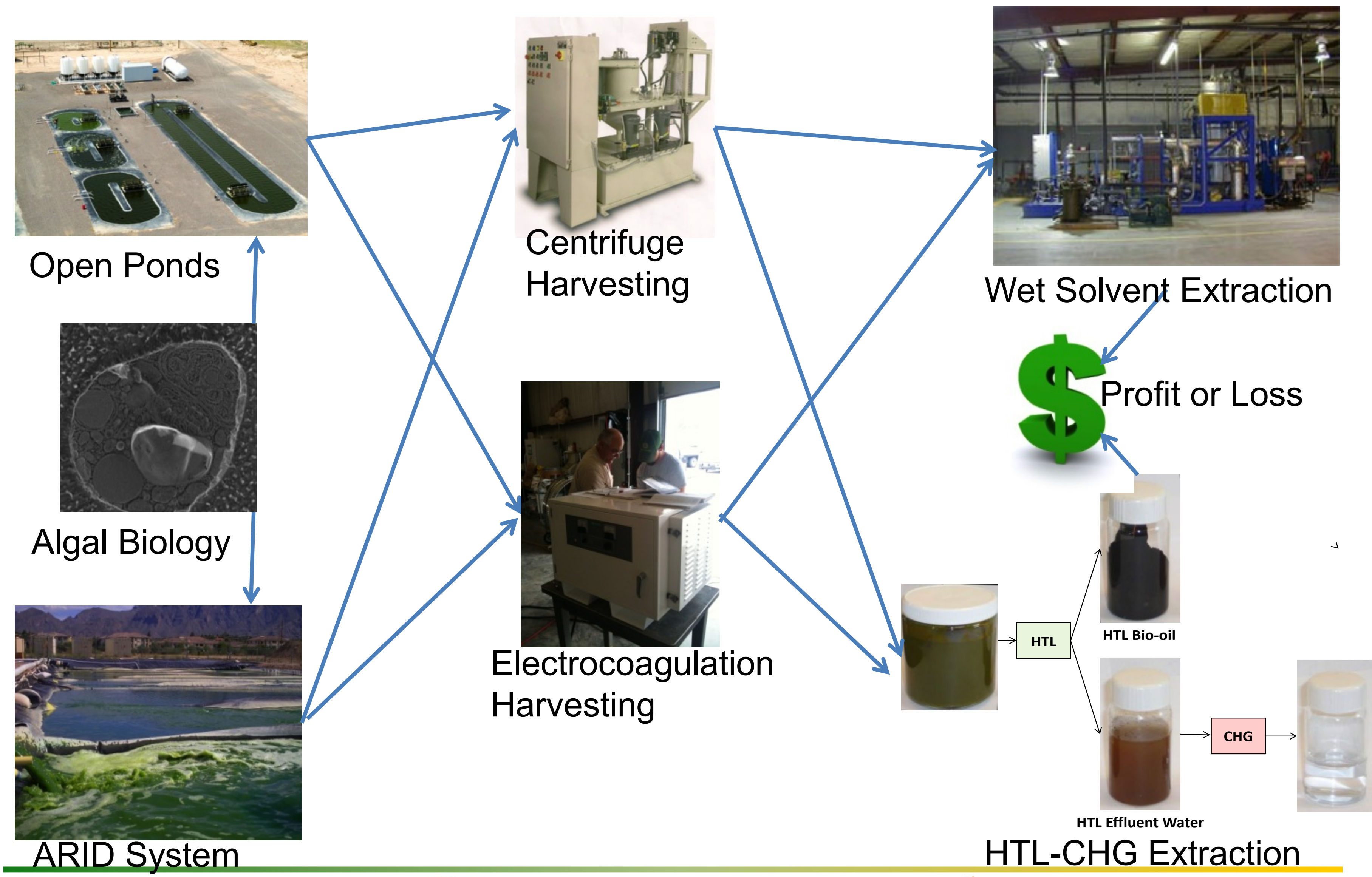

Economic Sustainability Analysis

- **Experimental data from NAABB researchers used in FARM to estimate contributions to reducing costs of production and improving economic sustainability**

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2. *Chlorella sorokiniana*-1412
3. Temperature-PAR based estimates

CULT

1. 12 g/m2/day in Open Pond
2. ARID Raceway design specifications

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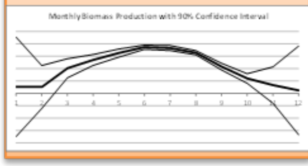
FARM

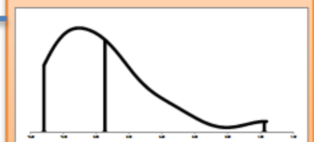
FARM Flowchart

Biomass Production



Biology

Prices of Outputs & Inputs, Rates of Inflation, Interest Rates



- Production
- Operating and Fixed Costs
- Receipts
- Debt Repayment
- Accounting
- Taxes
- Depreciation
- Machinery Replacement

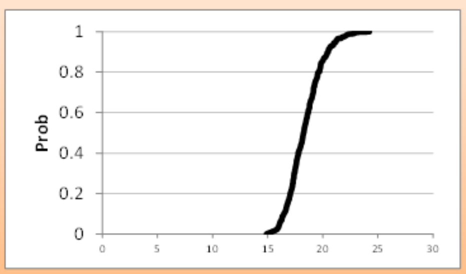
CAPEX & Debt Structure

Cultivation System

Extraction System

Harvesting System

P(Economic Success), Total Cost, Marginal Cost, Ending Cash, Financial Ratios…



Open Pond	Fractional Reductions in the CAPEX									
Fraction OPEX	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	3.0%
0.1	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	40.2%
0.2	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	97.2%
0.3	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%
0.4	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%
0.5	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	8.4%	100.0%
0.6	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	71.8%	100.0%
0.7	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	100.0%
0.8	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	100.0%
0.9	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	1.6%	100.0%	100.0%

Scenario Analysis Highlight NAABB Technologies

- Four technologies developed by NAABB are analyzed for a representative algae farm and compared to a base technology
- Where possible CAPEX and OPEX costs from DOE's Harmonized report were scaled based on BAT's annual biomass production levels for farm sites
- Pecos, TX and Tucson, AZ biomass, lipid, and water use probability distributions from BAT were used in the technology analyses and augmented for biomass production assumed for the advances reported by Algal Biology Team

Algae Farm Information for Scenario Analyses

	Base Farm
Total Hectares of Land	4,850
Total Hectares of Ponds	4,050
Total Volume of Ponds (AF)	9,855
Total Volume of Ponds (L)	12,156,211,201
Days of Operation	330
Total CAPEX	$1,270,255,769
Total OPEX Year 5	$739,780,301

Source: Extrapolated from DOE Harmonization report 2012

Technology Scenarios Analyzed

- **Base scenario represents pre-NAABB technologies and production systems**

- **Four technologies selected to highlight the NAABB contributions to technology for reducing lipid costs, and increasing economic viability**

- **Scenarios highlighted technologies coming from NAABB Teams:**
  - Algal Biology
  - Cultivation
  - Harvesting and Extraction

Base Plus the Five Scenarios Analyzed

	Base	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Products	Algae Crude Oil & LEA	Algae Crude Oil & LEA	Algae Crude Oil & Methane	Algae Crude Oil & Methane	Algae Crude Oil & Methane	Algae Crude Oil & Methane
Cultivation	Open Pond w/ Liners	Open Pond w/ Liners	Open Pond w/ Liners	Open Pond w/ Liners	ARID	ARID
Biology	Generic	Generic	Generic	GMO	Generic	GMO
Harvesting	Centrifuge	Electrocoa-gulation (EC)	Centrifuge	EC	EC	EC
Extraction	Wet Solvent	Wet Solvent	HTL-CHG	HTL-CHG	HTL-CHG	HTL-CHG
Nutrient Recycling	No	No	Yes	Yes	Yes	Yes
Biomass Production (Tons/Yr)	119,883	119,883	119,883	316,831	152,215	378,591
Crude Oil Production (Gallons/Yr)	4,679,762	5,095,741	15,006,224	43,184,240	20,747,054	51,602,173
Location	Pecos, TX	Pecos, TX	Pecos, TX	Pecos, TX	Tucson, AZ	Tucson, AZ

Algae Farm Risks

- Farms sell algae crude oil and lipid extracted algae (LEA) or methane depending on extraction technology
- Risk associated with algae farming was incorporated into the FARM model by simulating random values from BAT's probability distributions for biomass, lipid production and net water use
- Risk for price changes was incorporated by sampling from historical price probability distributions for input and output prices
- Each scenario simulated for 10 years and the planning horizon was repeated 500 iterations to incorporate full range of risk with best and worst cases appropriated weighted by risk of occurrence
- Repeated each scenario 100 times with systematic reductions in CAPEX and OPEX in 10% increments from zero to 90%

Scenarios Analyzed for Sustainability

- **Base Scenario**
  - Open pond cultivation with paddlewheels for mixing
  - Low algae production rates
  - Centrifuges for harvesting
  - Wet solvent extraction with LEA byproduct

- **Scenario 1 - Evaluates the improvements in harvesting technology**
  - Electrocoagulation (EC) replaces centrifuges
  - Otherwise Scenario 1 is identical to Base Scenario

- **Scenario 2 - Evaluates the improvements in extraction technology**
  - Hydro Thermal Liquefaction-Catalytic Hydro Gasification (HTL-CHG) instead of wet solvent extraction
  - Otherwise Scenario 2 is identical to Base Scenario

Scenarios Analyzed for Sustainability

- **Scenario 3 – Evaluates improvements in biology**
  - Combines the improvements in Scenarios 1 & 2 from harvesting and extraction, uses EC & HTL-CHG
  - Increased algae production rates (164% increase over baseline)

- **Scenario 4 - Evaluates ARID cultivation technology**
  - EC & HTL-CHG used for harvesting & extraction
  - Algae production rates (27% increase over baseline)

- **Scenario 5 - ARID cultivation with improved biology and low cost harvesting and extraction options**
  - EC & HTL-CHG used for harvesting & extraction
  - Increased algae production rates (216% increase over baseline)

Key Output Variables from FARM

- **Probability of Success – Probability that the farm business will earn an average internal rate of return greater than the investor's discount rate of 10%**

- **Marginal Cost (MC) of Production – Operating expense per gallon of lipid, ignoring all fixed costs**

- **Total Cost (TC) of Production – Marginal cost plus interest and dividend payments and depreciation per gallon**

- **Sensitivity Elasticity (E_S) – shows how output variables change with a 1% change in an exogenous cost or production variable, i.e., percentage change in MC change when harvesting CAPEX is reduced 1%**

Sustainability Base

- **There are no combinations of reductions in CAPEX and OPEX that result in a non-zero probability of economic success.**
- **Even with 90% reductions in CAPEX and OPEX the Total Cost ($/gallon) of lipid remains extremely high at $15.73/ gallon.**
- **Similarly, even with 90% reductions in CAPEX and OPEX the Marginal Cost ($/ gallon) of lipid remains extremely high at $13.11/ gallon.**

Probability of Economic Success

Open Pond	Fractional Reductions in the CAPEX							
Fraction OPEX	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.1	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.2	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.3	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.4	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.5	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.6	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.7	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.8	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.9	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Average Total Cost per Gallon for Lipid ($/Gallon)

Open Pond	Fractional Reductions in the CAPEX							
Fraction OPEX	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	220.43	213.75	207.06	200.37	193.69	187.00	180.32	173.63
0.1	202.83	196.15	189.47	182.80	176.12	169.44	162.76	156.09
0.2	185.23	178.56	171.89	165.22	158.55	151.88	145.21	138.54
0.3	167.63	160.96	154.30	147.64	140.98	134.32	127.66	121.00
0.4	150.02	143.37	136.72	130.07	123.41	116.76	110.11	103.45
0.5	132.42	125.78	119.13	112.49	105.84	99.20	92.55	85.91
0.6	114.82	108.18	101.55	94.91	88.27	81.64	75.00	68.36
0.7	97.22	90.59	83.96	77.33	70.70	64.08	57.45	50.82
0.8	79.62	73.00	66.38	59.76	53.14	46.52	39.90	33.27
0.9	62.02	55.40	48.79	42.18	35.57	28.95	22.34	15.73

Average Marginal Cost per Gallon for Lipid ($/Gallon)

Open Pond	Fractional Reductions in the CAPEX							
Fraction OPEX	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	131.51	131.45	131.38	131.32	131.26	131.20	131.14	131.08
0.1	118.36	118.30	118.25	118.19	118.14	118.08	118.03	117.97
0.2	105.21	105.16	105.11	105.06	105.01	104.96	104.91	104.86
0.3	92.05	92.01	91.97	91.93	91.88	91.84	91.80	91.75
0.4	78.90	78.87	78.83	78.79	78.76	78.72	78.68	78.65
0.5	65.75	65.72	65.69	65.66	65.63	65.60	65.57	65.54
0.6	52.60	52.58	52.55	52.53	52.50	52.48	52.46	52.43
0.7	39.45	39.43	39.42	39.40	39.38	39.36	39.34	39.32
0.8	26.30	26.29	26.28	26.26	26.25	26.24	26.23	26.22
0.9	13.15	13.14	13.14	13.13	13.13	13.12	13.11	13.11

Sustainability Scenario 1 - Harvesting

- **There are no combinations of reductions in CAPEX and OPEX that result in non-zero probability of economic success.**
- **Even with 90% reductions in CAPEX and OPEX the Total Cost ($/gallon) of lipid remains extremely high $12.55/gallon. Total cost reduced compared to Scenario 1 of $15.73. EC is an improvement over centrifuge.**
- **Even with 90% reductions in CAPEX and OPEX the Marginal Cost ($/gallon) of lipid remains extremely high, but is improved over Scenario 1, $11.92/gallon.**

Probability of Economic Success

Open Pond	Fractional Reductions in the CAPEX							
Fraction OPEX	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.1	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.2	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.3	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.4	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.5	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.6	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.7	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.8	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.9	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Average Total Cost per Gallon for Lipid ($/Gallon)

Open Pond	Fractional Reductions in the CAPEX							
Fraction OPEX	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	191.59	186.54	181.49	176.44	171.39	166.34	161.29	156.24
0.1	175.58	170.54	165.49	160.45	155.41	150.36	145.32	140.28
0.2	159.57	154.53	149.50	144.46	139.42	134.38	129.35	124.31
0.3	143.56	138.53	133.50	128.47	123.43	118.40	113.37	108.34
0.4	127.55	122.52	117.50	112.47	107.45	102.42	97.40	92.37
0.5	111.54	106.52	101.50	96.48	91.46	86.44	81.43	76.41
0.6	95.53	90.51	85.50	80.49	75.48	70.46	65.45	60.44
0.7	79.51	74.51	69.50	64.50	59.49	54.48	49.48	44.47
0.8	63.50	58.50	53.50	48.50	43.50	38.50	33.50	28.50
0.9	47.49	42.50	37.50	32.51	27.52	22.52	17.53	12.55

Average Marginal Cost per Gallon for Lipid ($/Gallon)

Open Pond	Fractional Reductions in the CAPEX							
Fraction OPEX	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	119.55	119.50	119.46	119.41	119.36	119.32	119.27	119.22
0.1	107.59	107.55	107.51	107.47	107.43	107.38	107.34	107.30
0.2	95.64	95.60	95.56	95.53	95.49	95.45	95.41	95.38
0.3	83.68	83.65	83.62	83.59	83.55	83.52	83.49	83.46
0.4	71.73	71.70	71.67	71.65	71.62	71.59	71.56	71.53
0.5	59.77	59.75	59.73	59.70	59.68	59.66	59.63	59.61
0.6	47.82	47.80	47.78	47.76	47.74	47.73	47.71	47.69
0.7	35.86	35.85	35.84	35.82	35.81	35.79	35.78	35.77
0.8	23.91	23.90	23.89	23.88	23.87	23.86	23.85	23.84
0.9	11.95	11.95	11.95	11.94	11.94	11.93	11.93	11.92

Sustainability Scenario 2 - Extraction

- **HTL-CHG instead of wet solvent extraction results in six acceptable probabilities of success, but only if significant reductions are made in CAPEX and OPEX.**
- **TC per gallon of lipid much lower compared to previous scenarios. In this comparison, HTL-CHG is much better than wet solvent extraction, with TC less than $4.00/gallon.**
- **If OPEX can be reduced by 50% and CAPEX can be reduced 70%, algal lipids could be competitive with fossil crude oil.**

Probability of Economic Success

Open Pond	Fractional Reductions in the CAPEX							
Fraction OPEX	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.1	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.2	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.3	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.4	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.5	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.4%
0.6	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	93.4%
0.7	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%
0.8	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	78.0%	100.0%
0.9	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	100.0%

Average Total Cost per Gallon for Lipid ($/Gallon)

Open Pond	Fractional Reductions in the CAPEX							
Fraction OPEX	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	21.54	19.45	17.36	15.27	13.18	11.10	9.01	6.92
0.1	20.74	18.65	16.57	14.48	12.39	10.31	8.22	6.14
0.2	19.94	17.85	15.77	13.69	11.60	9.52	7.44	5.36
0.3	19.13	17.05	14.97	12.89	10.81	8.73	6.66	4.62
0.4	18.33	16.26	14.18	12.10	10.02	7.96	5.92	3.93
0.5	17.53	15.46	13.38	11.31	9.25	7.22	5.24	3.28
0.6	16.73	14.66	12.59	10.54	8.52	6.55	4.59	2.64
0.7	15.93	13.87	11.82	9.82	7.85	5.90	3.95	2.08
0.8	15.14	13.10	11.11	9.15	7.20	5.25	3.35	1.68
0.9	14.38	12.40	10.45	8.50	6.55	4.63	2.94	1.27

Average Marginal Cost per Gallon for Lipid ($/Gallon)

Open Pond	Fractional Reductions in the CAPEX							
Fraction OPEX	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	4.81	4.79	4.78	4.76	4.74	4.72	4.70	4.68
0.1	4.33	4.32	4.30	4.28	4.26	4.25	4.23	4.21
0.2	3.85	3.84	3.82	3.81	3.79	3.77	3.76	3.74
0.3	3.37	3.36	3.34	3.33	3.32	3.30	3.29	3.28
0.4	2.89	2.88	2.87	2.85	2.84	2.83	2.82	2.81
0.5	2.41	2.40	2.39	2.38	2.37	2.36	2.35	2.34
0.6	1.93	1.92	1.91	1.90	1.89	1.89	1.88	1.87
0.7	1.44	1.44	1.43	1.43	1.42	1.42	1.41	1.40
0.8	0.96	0.96	0.96	0.95	0.95	0.94	0.94	0.94
0.9	0.48	0.48	0.48	0.48	0.47	0.47	0.47	0.47

Sustainability Scenario 3 - Biology

NAABB
National Alliance For Advanced Biofuels and Bio-products

- **Combining EC & HTL-CHG with increased biomass production with the same resources results in several acceptable probabilities of success, when combined with reductions in CAPEX and OPEX.**

- **The TC per gallon of lipid is much lower compared to previous scenarios, less than $4.00/gallon, for the same assumed reductions in CAPEX and OPEX.**

- **Algal lipids can be competitive with fossil fuel with reductions in costs and NAABB's improvements in harvesting, extraction, and biology.**

Probability of Economic Success

Open Pond	Fractional Reductions in the CAPEX							
Fraction OPEX	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.1	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.2	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.3	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.4	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.5	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.6	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	1.4%	63.6%
0.7	0.0%	0.0%	0.0%	0.0%	0.6%	50.0%	99.8%	100.0%
0.8	0.0%	0.0%	0.2%	37.6%	99.6%	100.0%	100.0%	100.0%
0.9	0.0%	21.6%	99.6%	100.0%	100.0%	100.0%	100.0%	100.0%

Average Total Cost per Gallon for Lipid ($/Gallon)

Open Pond	Fractional Reductions in the CAPEX							
Fraction OPEX	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	10.33	9.65	8.96	8.28	7.59	6.91	6.22	5.54
0.1	9.58	8.89	8.21	7.52	6.84	6.16	5.47	4.79
0.2	8.82	8.14	7.45	6.77	6.09	5.41	4.74	4.06
0.3	8.06	7.38	6.71	6.03	5.36	4.69	4.03	3.37
0.4	7.32	6.65	5.99	5.33	4.67	4.01	3.36	2.72
0.5	6.62	5.96	5.31	4.67	4.02	3.37	2.73	2.09
0.6	5.96	5.32	4.68	4.03	3.39	2.75	2.11	1.47
0.7	5.33	4.69	4.05	3.41	2.77	2.13	1.50	0.91
0.8	4.71	4.07	3.43	2.79	2.17	1.61	1.13	0.69
0.9	4.09	3.46	2.87	2.36	1.88	1.42	0.97	0.57

Average Marginal Cost per Gallon for Lipid ($/Gallon)

Open Pond	Fractional Reductions in the CAPEX							
Fraction OPEX	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	1.89	1.89	1.88	1.87	1.87	1.86	1.86	1.85
0.1	1.70	1.70	1.69	1.69	1.68	1.68	1.67	1.66
0.2	1.51	1.51	1.50	1.50	1.49	1.49	1.48	1.48
0.3	1.33	1.32	1.32	1.31	1.31	1.30	1.30	1.29
0.4	1.14	1.13	1.13	1.12	1.12	1.12	1.11	1.11
0.5	0.95	0.94	0.94	0.94	0.93	0.93	0.93	0.92
0.6	0.76	0.75	0.75	0.75	0.75	0.74	0.74	0.74
0.7	0.57	0.57	0.56	0.56	0.56	0.56	0.56	0.55
0.8	0.38	0.38	0.38	0.37	0.37	0.37	0.37	0.37
0.9	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.18

Sustainability Scenario 4 - Cultivation

- **ARID cultivation system, along with EC & HTL-CHG returns several non-zero probabilities of economic success, indicating that it could be a viable cultivation system.**

- **With severe reductions in CAPEX and OPEX, e.g., 70% CAPEX and 70% OPEX reduction, algal fuels can become competitive with fossil fuel at $3.51/gallon.**

- **Similarly, with discounts in OPEX, e.g., 20% or greater OPEX reductions, algal fuels can become competitive with current fuel sources, less than $2.00/gallon.**

Probability of Economic Success

Open Pond	Fractional Reductions in the CAPEX							
Fraction OPEX	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	100.0%
0.1	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	3.2%	100.0%
0.2	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	31.6%	100.0%
0.3	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	89.8%	100.0%
0.4	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	99.8%	100.0%
0.5	0.0%	0.0%	0.0%	0.0%	0.0%	0.6%	100.0%	100.0%
0.6	0.0%	0.0%	0.0%	0.0%	0.0%	11.4%	100.0%	100.0%
0.7	0.0%	0.0%	0.0%	0.0%	0.0%	64.6%	100.0%	100.0%
0.8	0.0%	0.0%	0.0%	0.0%	0.0%	97.8%	100.0%	100.0%
0.9	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	100.0%	100.0%

Average Total Cost per Gallon for Lipid ($/Gallon)

Open Pond	Fractional Reductions in the CAPEX							
Fraction OPEX	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	12.68	11.17	9.67	8.18	6.72	5.29	3.89	2.57
0.1	12.33	10.83	9.34	7.86	6.43	5.02	3.62	2.37
0.2	11.99	10.49	9.01	7.56	6.15	4.74	3.36	2.17
0.3	11.65	10.16	8.70	7.27	5.87	4.47	3.15	1.97
0.4	11.31	9.84	8.40	6.99	5.59	4.20	2.94	1.77
0.5	10.98	9.53	8.12	6.72	5.32	3.94	2.74	1.58
0.6	10.67	9.24	7.84	6.44	5.04	3.72	2.54	1.40
0.7	10.36	8.95	7.56	6.16	4.77	3.51	2.35	1.29
0.8	10.07	8.67	7.28	5.89	4.51	3.31	2.17	1.19
0.9	9.79	8.40	7.01	5.62	4.28	3.11	2.00	1.04

Average Marginal Cost per Gallon for Lipid ($/Gallon)

Open Pond	Fractional Reductions in the CAPEX							
Fraction OPEX	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	2.43	2.42	2.40	2.39	2.37	2.36	2.35	2.33
0.1	2.19	2.17	2.16	2.15	2.14	2.12	2.11	2.10
0.2	1.94	1.93	1.92	1.91	1.90	1.89	1.88	1.87
0.3	1.70	1.69	1.68	1.67	1.66	1.65	1.64	1.63
0.4	1.46	1.45	1.44	1.43	1.42	1.42	1.41	1.40
0.5	1.21	1.21	1.20	1.19	1.19	1.18	1.17	1.17
0.6	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.93
0.7	0.73	0.72	0.72	0.72	0.71	0.71	0.70	0.70
0.8	0.49	0.48	0.48	0.48	0.47	0.47	0.47	0.47
0.9	0.24	0.24	0.24	0.24	0.24	0.24	0.23	0.23

Sustainability Scenario 5 – Cultivation and Biology

- **ARID cultivation system, with biomass production increases, EC & HTL-CHG returns the most non-zero probabilities of economic success, but cuts in CAPEX and OPEX will be necessary.**
- **With reductions in CAPEX and OPEX algal fuels can be competitive with fossil fuels. A 40% reduction in CAPEX and 30% reduction in OPEX has TC of \$3.14/gallon.**
- **With the given improvements in biological, harvesting, and extraction technologies algal production can become a viable source of crude oil.**

Probability of Economic Success

Open Pond	Fractional Reductions in the CAPEX							
Fraction OPEX	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	0.0%	0.0%	0.0%	7.2%	97.0%	100.0%	100.0%	100.0%
0.1	0.0%	0.0%	0.0%	41.4%	100.0%	100.0%	100.0%	100.0%
0.2	0.0%	0.0%	1.8%	87.6%	100.0%	100.0%	100.0%	100.0%
0.3	0.0%	0.0%	18.2%	100.0%	100.0%	100.0%	100.0%	100.0%
0.4	0.0%	0.2%	64.2%	100.0%	100.0%	100.0%	100.0%	100.0%
0.5	0.0%	5.0%	97.0%	100.0%	100.0%	100.0%	100.0%	100.0%
0.6	0.0%	36.6%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
0.7	1.0%	85.4%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
0.8	14.2%	99.8%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
0.9	57.4%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Average Total Cost per Gallon for Lipid (\$/Gallon)

Open Pond	Fractional Reductions in the CAPEX							
Fraction OPEX	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	4.85	4.26	3.67	3.08	2.50	1.92	1.40	0.93
0.1	4.67	4.08	3.49	2.90	2.33	1.79	1.31	0.85
0.2	4.49	3.90	3.31	2.73	2.19	1.69	1.23	0.82
0.3	4.31	3.72	3.14	2.58	2.08	1.61	1.16	0.83
0.4	4.12	3.54	2.98	2.47	1.99	1.53	1.14	0.83
0.5	3.94	3.38	2.86	2.37	1.90	1.47	1.12	0.77
0.6	3.78	3.25	2.76	2.28	1.82	1.43	1.07	0.69
0.7	3.64	3.14	2.66	2.19	1.76	1.38	0.98	0.62
0.8	3.53	3.05	2.57	2.11	1.69	1.29	0.89	0.55
0.9	3.43	2.95	2.47	2.02	1.60	1.19	0.80	0.45

Average Marginal Cost per Gallon for Lipid (\$/Gallon)

Open Pond	Fractional Reductions in the CAPEX							
Fraction OPEX	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	1.22	1.21	1.20	1.20	1.19	1.19	1.18	1.18
0.1	1.09	1.09	1.08	1.08	1.07	1.07	1.06	1.06
0.2	0.97	0.97	0.96	0.96	0.95	0.95	0.94	0.94
0.3	0.85	0.85	0.84	0.84	0.83	0.83	0.83	0.82
0.4	0.73	0.73	0.72	0.72	0.72	0.71	0.71	0.71
0.5	0.61	0.60	0.60	0.60	0.60	0.59	0.59	0.59
0.6	0.49	0.48	0.48	0.48	0.48	0.47	0.47	0.47
0.7	0.36	0.36	0.36	0.36	0.36	0.36	0.35	0.35
0.8	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24
0.9	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12

Sustainability Results for a 4,850 ha Algae Farm

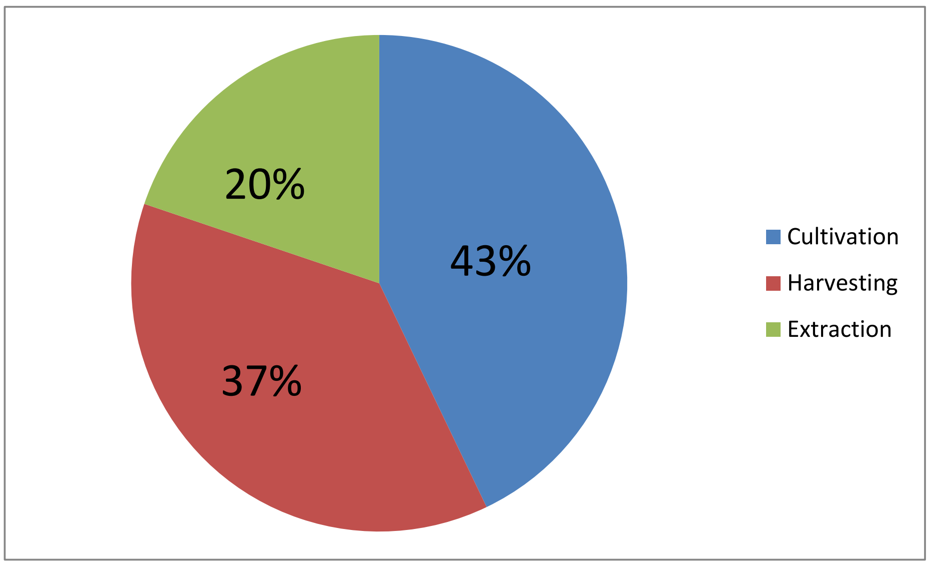
	Base	Scenario 1 Harvesting	Scenario 2 Extraction	Scenario 3 Harv/Extr Biology	Scenario 4 Harv/Extr Cultivation	Scenario 5 Harv/Extr Cultivation Biology
Reduction in CAPEX	90%	90%	80%	70%	70%	40%
Reduction in OPEX	90%	90%	80%	70%	70%	50%
P(Success)	0.0 – 0.0	0.0 – 0.0	0.0 – 78.0%	0.0 – 50%	0.0 – 64.6%	0.0 – 97.0%
Total Cost $/gal	233.80- **15.73**	201.69 – **12.55**	21.54 – **3.35**	10.33 – **2.15**	12.68 – **3.51**	4.85 – **2.86**

Range of costs reported above are for zero reductions in CAPEX and OPEX vs. the smallest reduction in CAPEX and OPEX to achieve economic viability

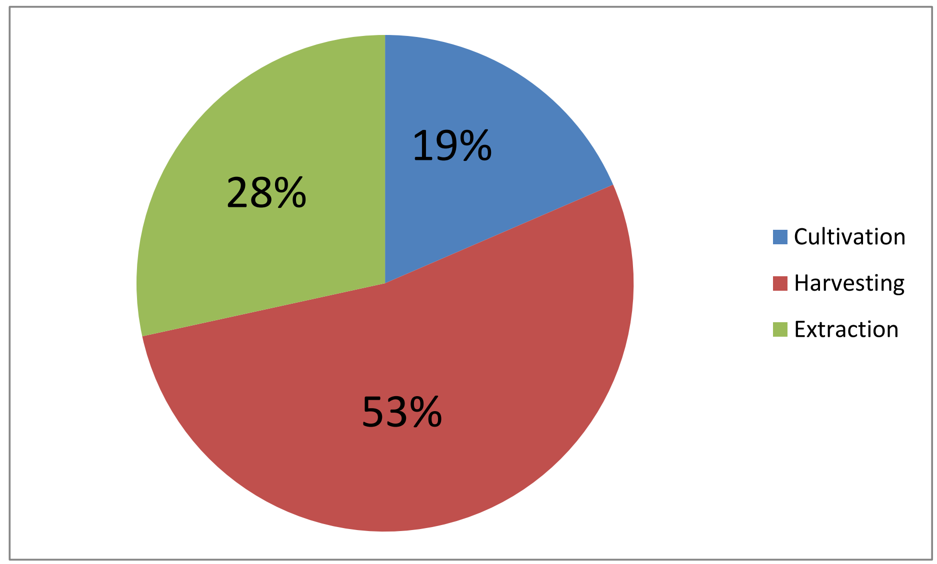
CAPEX and OPEX for Scenario 3

- **Cultivation, harvesting, and extraction CAPEX are all major cost sources**

- **Costs have to be dramatically cut in all areas to insure profitability**



CAPEX



OPEX

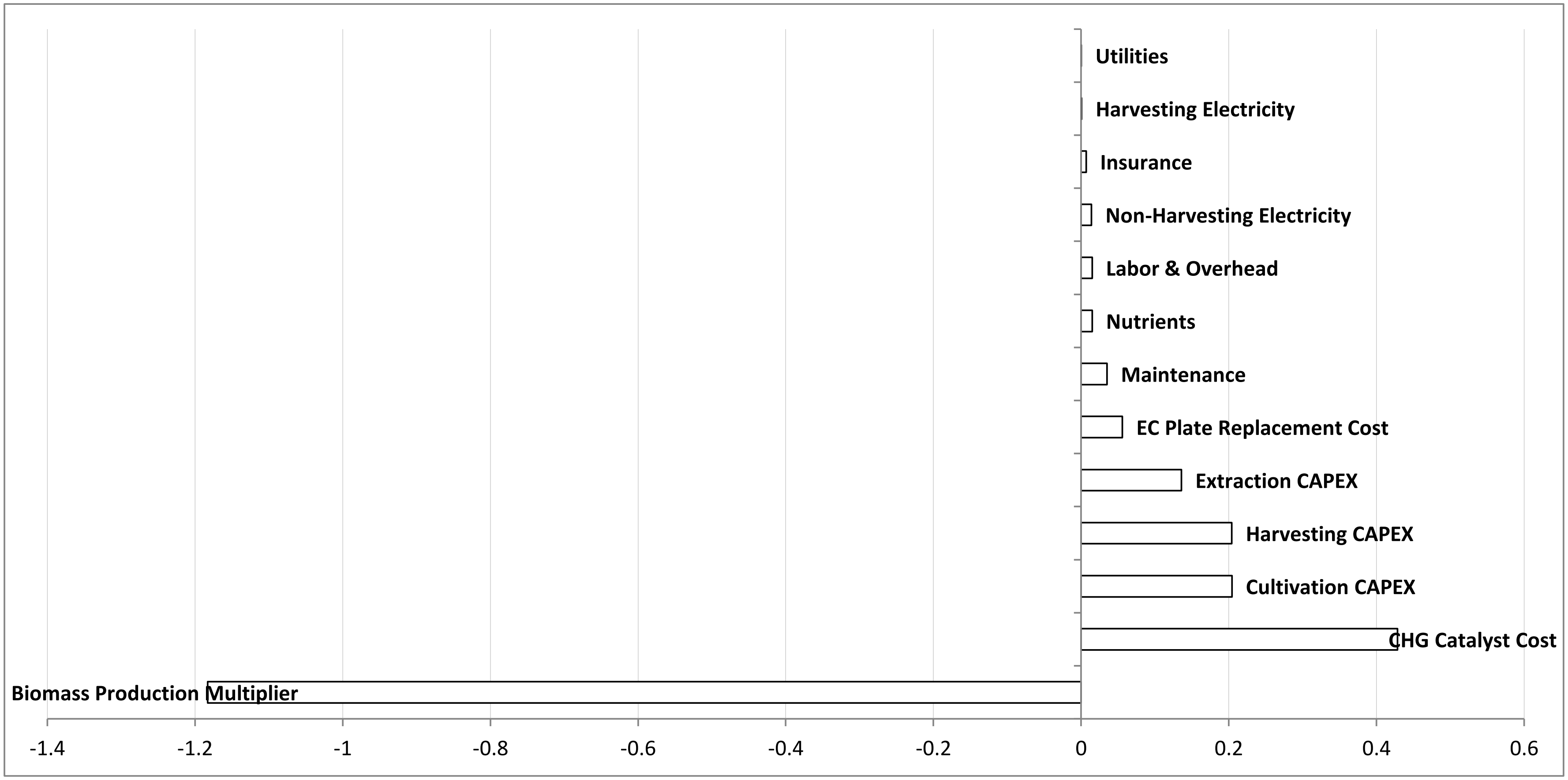
Guide to Reducing Costs

- Cost reductions will be essential for a profitable algal industry
- FARM includes a tool for determining where cost reductions will be most beneficial
- Sensitivity elasticities in the model show the percentage reduction in total cost of production for a one percentage reduction in a particular input cost
- Also used to show percentage increases in income for a one percent increase in biomass production or a one percent decrease in costs

Sensitivity Elasticity – Total Costs Scenario 3

For Scenario 3:

a 1% decrease in harvesting CAPEX reduces TC 0.2%
a 1% decrease in extraction catalyst cost TC 0.45%
a 1% increase in biomass production reduced TC 1.18%

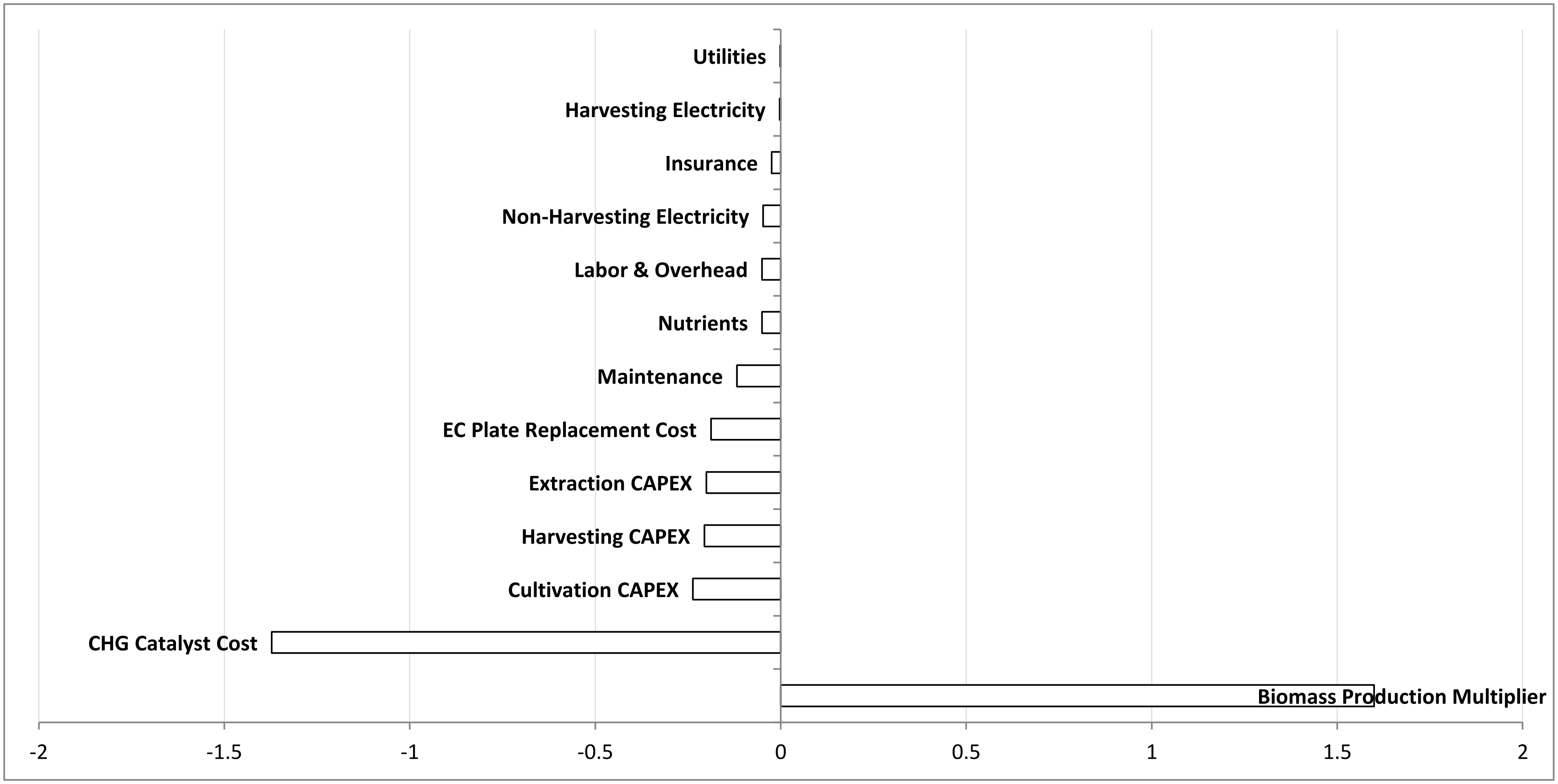


Fractional Changes in Total Costs for a 1% change

Sensitivity Elasticity – Net Cash Income Scenario 3

For Scenario 3:

a 1% decrease in harvesting CAPEX increases NCI 0.25%
a 1% decrease in extraction catalyst cost increases NCI 1.45%
a 1% increase in biomass production increases NCI 1.65%



Fractional Changes in Total Costs for a 1% change

Critical Success Factors for Sustainability

- **Increasing biomass productivity and crop protection 10% without changing CAPEX and OPEX**
  - Increases net cash income 16%

- **10% Reduction in harvesting CAPEX and OPEX ($86.1 million)**
  - Increases net cash income 4.5%
  - A 10% reduction in harvesting CAPEX is $ 46.9 million
  - A 10% reduction in harvesting OPEX is $ 39.2 million

- **10% Reduction in extraction CAPEX and OPEX ($60.9million)**
  - Increases net cash income 16.5%
  - A 10% reduction in extraction CAPEX is $25.4 million
  - A 10% reduction in extraction OPEX is $35.5 million

- **10% Reduction in cultivation CAPEX and OPEX ($78.7 million)**
  - Increases net cash income 3%
  - A 10% reduction in cultivation CAPEX is $54.6 million
  - A 10% reduction in cultivation OPEX is $24.1 million

Cut CAPEX and OPEX

NAABB
National Alliance For Advanced Biofuels and Bio-products

Future Work

- **Use data for cultivation, characterization, and processes generated during the final months of NAABB to create empirically based estimates of:**
  - Production potential and viability based on outdoor cultivation data
  - Impact of cultivation variables on production of biomass and lipids (quality and quantity)
  - Use APA projected biomass production in FARM to generate estimates of profitability based on field-scale data
- **Scenario analyses using FARM extended to additional technologies developed by NAABB that were not presented in this report**
  - Water quality impacts on production
  - Produced water algae production
  - Alternative media formulas and costs
  - Alternative harvesting technologies
  - Additional biology applications using newer GMO strains

Questions on Scenario Analysis?