Net Energy and Greenhouse Gas Emissions Evaluation of Biodiesel Derived from Microalgae

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Overview

- Advantages and Disadvantages of Algae
- Goals and Scope
- Assessment
- Model
- Results and Conclusions
- Future Works

Advantages of Algae

– Photosynthetic efficiency (6-20%) vs. terrestrial (0.5-2%)

– Lipid production (5,000 gal/acre) vs. soybean oil yield (4,600 gal/acre)

– Water-borne that allows ready access to nutrients and concentrated CO_2

– Low environmental requirements

  - Broad range of water salinity
  - Low quality land for culture

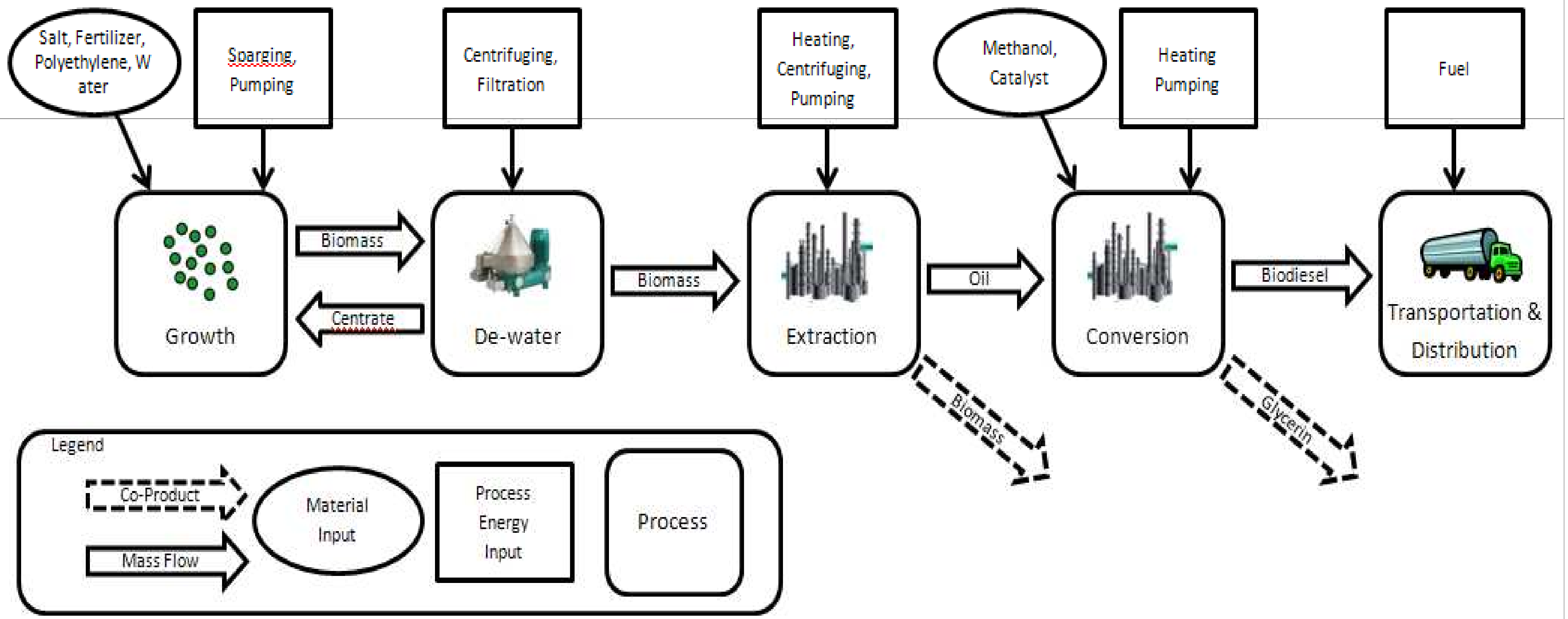
Disadvantages of Algae

- A built environment to support algae culture
- Initial capital investment
- Maintenance and material costs
- Energy use
- Water use
- Fertilizer use

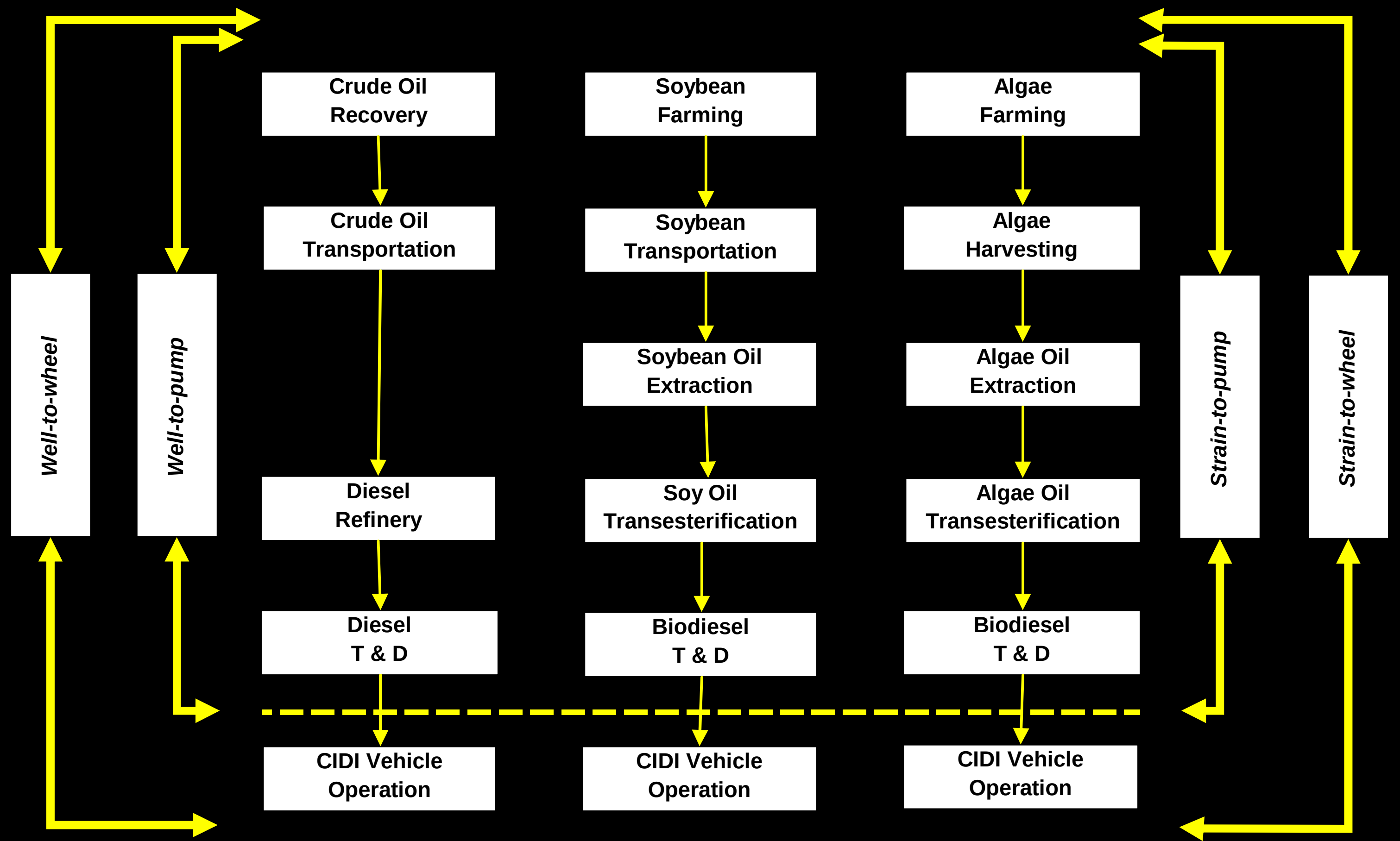
Goals

- Assessment of algae-to-biofuel process for information and data gaps
- Potential modes of algae LCA improvement
- Life-cycle comparison to other transportation fuels - petroleum diesel and soy-based biodiesel
- Scalability assessment

Microalgae process & LCA overview



Scope – *Strain-to-Pump*



Assessment

- Functional unit: unit of energy output per cycle
- Primary metrics:
  - Net Energy Ratio (NER): energy consumed per energy produced
  - GHG emissions: computation of CO_2, CH_4 and N_2O
  - Scalability of Inputs and Products: based on 40 billion gallons of biofuel per year (US DOE 2030 goal)

Assessment

- Material: Argonne National Laboratory (ANL) GREET model
  - Lifecycle model for transportation fuel (database of U.S. average conditions)
  - Modifications made to simulate energy and material inventories of algae-to-biodiesel process

Assessment

Study assumptions

- No capital energy expenditures
- No thermal regulation energy (location/season)
- No transportation for CO_2-to-plant, feedstock-to-intermediate-storage
- Co-product credits
  - Displacement method
  - Energy- and Market-value allocation methods

Model

(1) Detailed engineering model for stages

- Integration and validation of process through literature and pilot plant
- Growth, dewater and extraction modeling and data collection
  - Process material & energy inputs and outputs
  - Growth rate of 25 $g.m^{-2}.day^{-1}$ and oil content of 50% w/w
- Industrial scale (315 ha)
- *Nannochloropsis sp*

Model

(2) GREET for generic model for oil conversion, transportation & distribution (U.S. average conditions)

- Petroleum diesel and soybean-based biodiesel
- Upstream material energy and emission data
- Conversion and emission data

(3) Modified model of GREET for assessment of lifecycle NER and GHG emissions

- Salt (media): energy and GHG emissions from literature

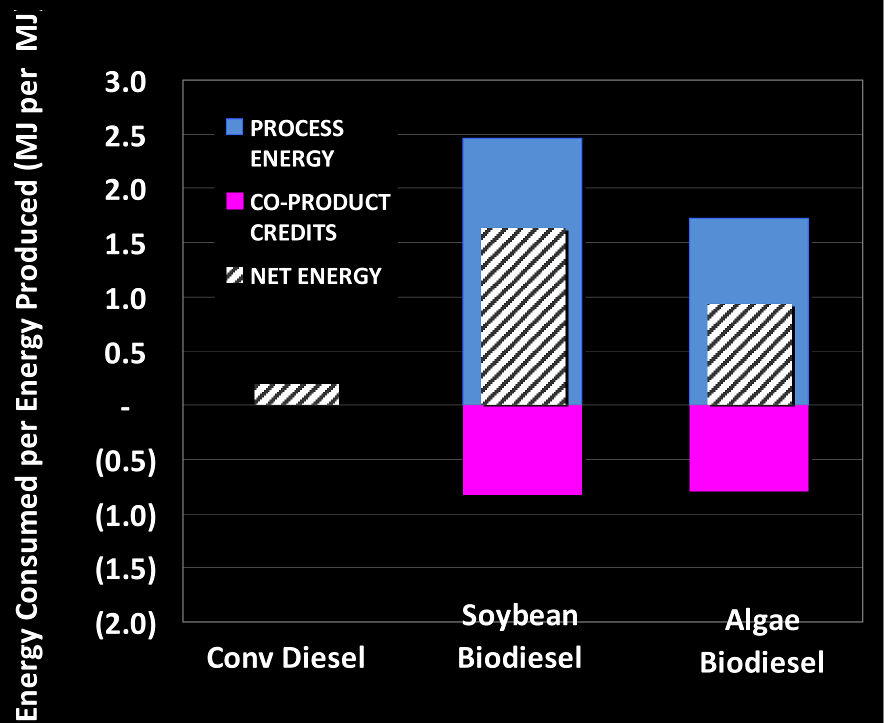
Colorado State University

Results – Process

STAGE/Inputs	VALUE	UNITS
GROWTH STAGE		
Photosynthetic area per facility area	0.80	ha/ha
Salt consumption	134	g/kg dry algae
Nitrogen fertilizer consumption	147	g/kg dry algae
Phosphorus fertilizer consumption	20	g/kg dry algae
Polyethylene consumption	1.17	m^3/ha
Diesel fuel consumption	10	L/ha
Electricity consumption	41,404	kWh/ha
Algae biomass yield	91,000	kg/ha
DEWATER STAGE		
Electricity use	30,788	kWh/ha
EXTRACTION STAGE		
Natural gas consumption	141,994	MJ/ha
Electricity consumption	12,706	kWh/ha
Extracted oil yield	43,009	L/ha
CONVERSION STAGE		
Natural Gas consumption	2.10	MJ/kg biodiesel
Electricity consumption	0.03	kWh/kg biodiesel
Methanol consumption	0.10	g/kg biodiesel
Sodium hydroxide consumption	0.005	g/kg biodiesel
Sodium methoxide consumption	0.0125	g/kg biodiesel
Hydrochloric acid consumption	0.0071	g/kg biodiesel
TRANSPORTATION & DISTRIBUTION		
Diesel consumption	0.0094	L/kg biodiesel

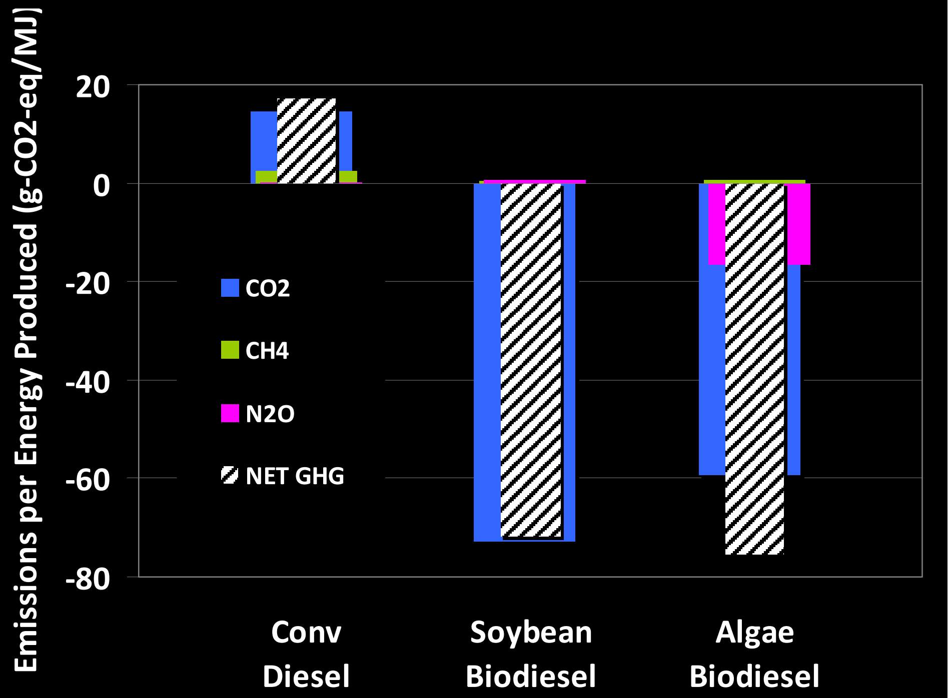
Results – Net Energy Ratio

Stage	Conventional Diesel	Soybean Biodiesel	Microalgae Biodiesel
Crude oil recovery*	0.053	-	-
Growth*	-	0.32	0.73
Dewater*	-	-	0.17
Oil extraction*	-	0.46	0.21
Fuel conversion*	0.13	0.17	0.17
Feedstock input*	-	1.50	0.43
Transportation & Distribution*	1.8E-7	0.01	0.01
Co-product credits*	-	(0.83)	(0.79)
Total NER**	**0.19**	**1.64**	**0.93**



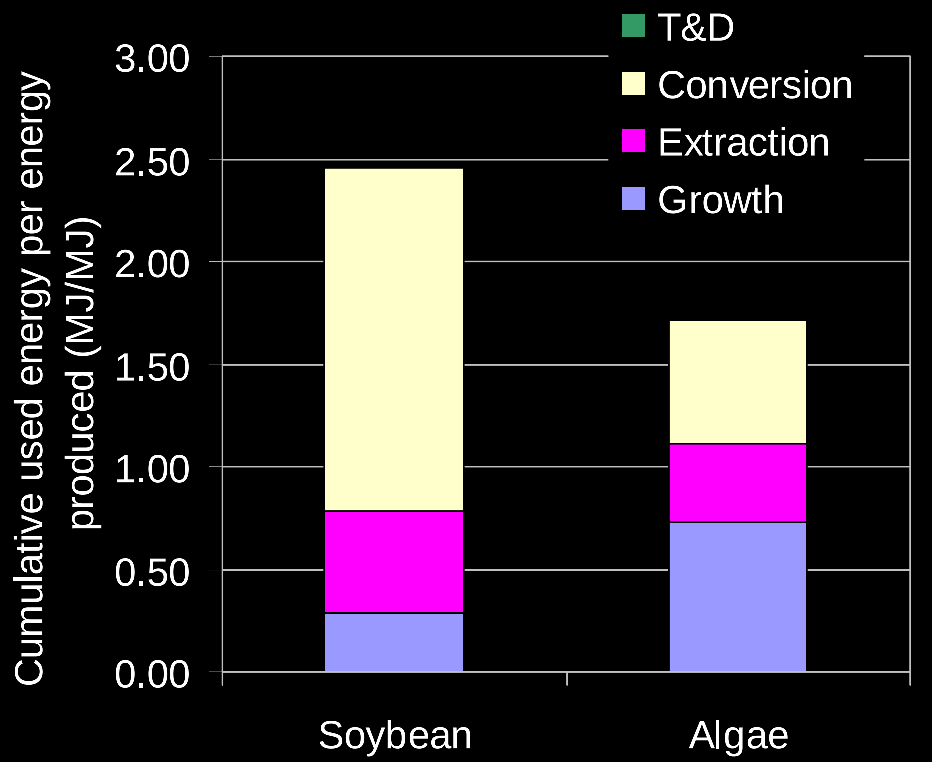
Results – GHG Emissions

	Conventional Diesel	Soybean Biodiesel	Microalgae Biodiesel
CO_2 (g/MJ)	14.69	-72.73	-59.49
CH_4 (g/MJ)	2.48	0.42	0.74
N_2O (g/MJ)	0.07	0.58	-16.54
Net "strain to pump" GHG ($gCO_{2\text{-}eq}$/MJ)	**17.24**	**-71.73**	**-75.29**



Results – LC Cumulative Energy

- **Growth stage**: 0.73 MJ/MJ (42% of algae LC cumulative energy) compared to 0.29 MJ/MJ (12% of soybean LC cumulative energy)
- **Electricity**: 36% of LC process energy consumption
- **N-based fertilizer**: 26% of LC cumulative energy



Co-Product Credits

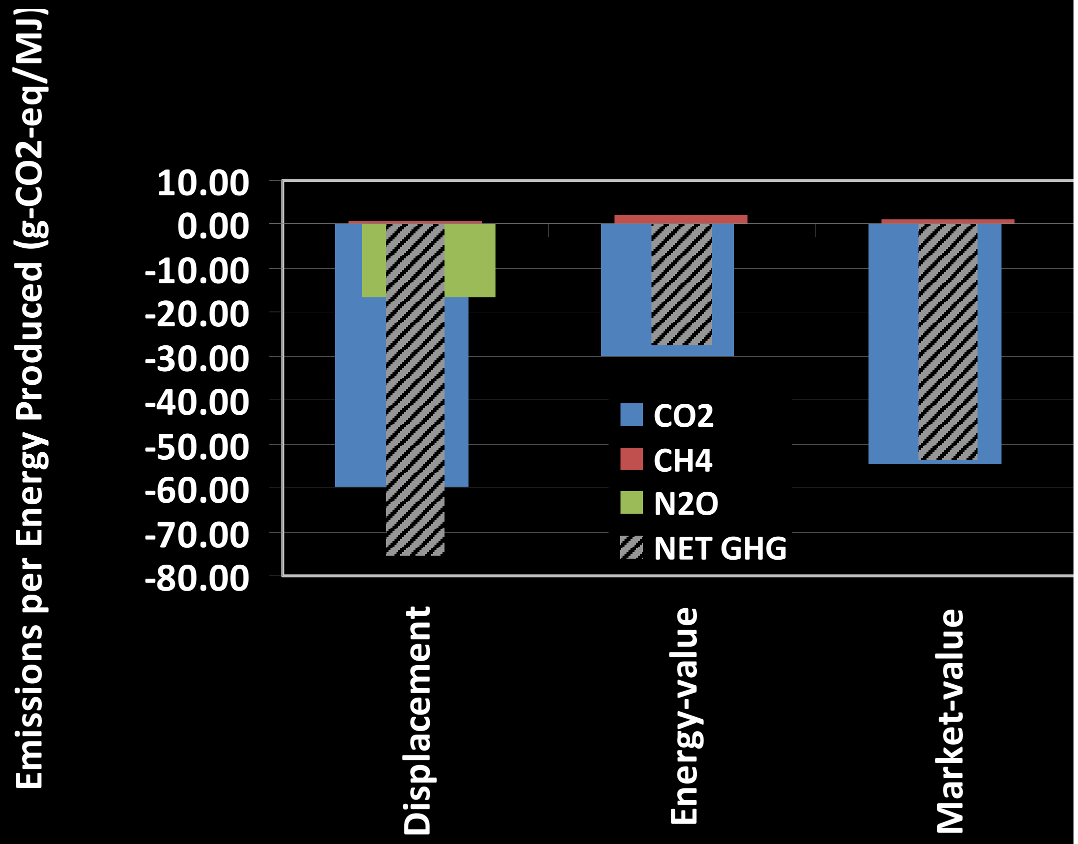
- Mass Displacement
  - Ratio of protein displacement: 1.3
    - Before oil extraction: 29%
    - After oil extraction: 36.7%

- Energy-value Allocation

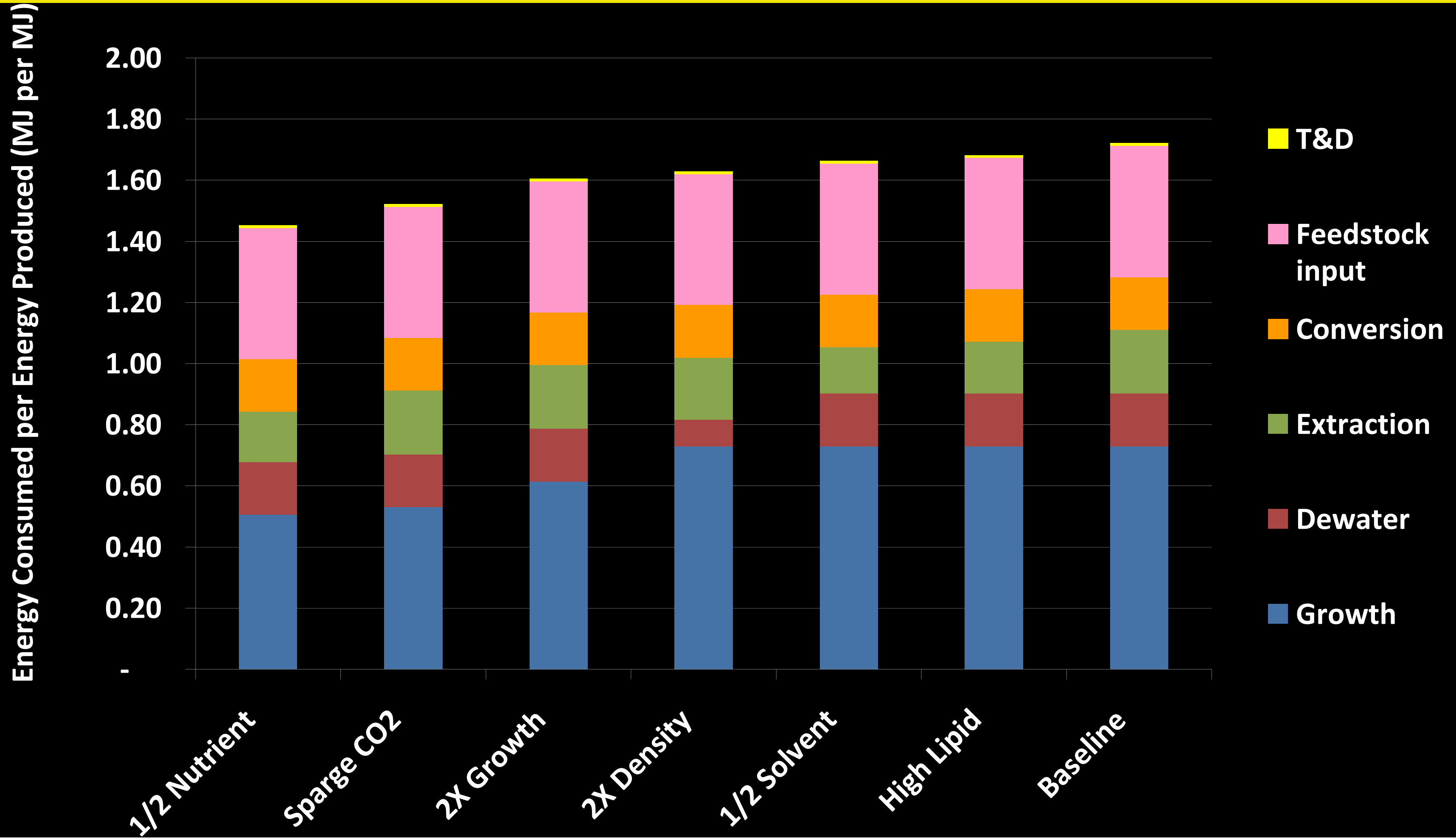
-Algae extract as co-firing material in power plant

- Market-value Allocation

- Algae extract as fish feed at $1.87/Kg



Results – Process Sensitivity



Scalability Analysis

Scalability analysis was performed to produce algae biodiesel to meet 18% of U.S. Transportation needs (EIA 2009)

- 151 billion cubic meters/yr of algae biodiesel

Results - Scalability

METRIC	PROJECTED REQUIREMENT	NOTES
Land Required	4.41x10^6 ha	16% of Colorado Land Area (0.45% of US Land Area) (U.S. Census Bureau 2009)
CO_2 Consumption	8.17 x10^{11} kg/yr	32% of CO_2 from US Power Generation (EIA 2007)
Natural Gas Consumption	1.39 x10^{11} kWh/yr	2% of US production (EIA 2009)

Results - Scalability

METRIC	PROJECTED REQUIREMENT	NOTES
Electricity Consumption	2.77 $x10^{11}$ kWh/yr	7%of US production (EIA 2007)
Algae Extract Co-Product Production	6.3$x10^{8}$kg/yr	11% of NOAA U.S. Aquaculture Outlook for 2025 (Kim et al 1992; U.S. Dept Commerce 2009)
Water Consumption	5.07 $x10^{9}$ m^3/yr	Sea water and brackish water are usable. It'll depend on local water sources

Results - Scalability

METRIC	PROJECTED REQUIREMENT	NOTES
Nitrogen Consumption	4.71 x10^7 ton/yr	1900% of US urea production (U.S. Census Bureau 2009)
Glycerin Co-product Production	2.1 x10^7 ton/yr	7500% of North American production (EIA 2007)

Conclusions

Algae biodiesel has strong potential as alternative to 1st generation biofuels:

- Robust net GHG reduction: 75.3 $gCO_{2\text{-}eq}$ / MJ produced
- Marginal yet positive benefit in terms of NER: 0.93 MJ used/MJ produced
- No competition for quality land
- Future/potential developments
  - Sensitivity to co-product allocation
- Downside:
  - High use of Nitrogen based fertilizer
  - Competition for water (maybe)
  - Low sensitivity to process variability

Future works

- Assessment of capital energy in the LCA
- Development of alternative Nitrogen sources (reuse/recycle, wastewater)
- Development of market use/value for algae co-products (animal feed, co-firing material)
- Evaluation of land use change (d/i)
- Additional work for sustainability study:
  - Water footprint

THANKS FOR YOUR ATTENTION!