Life Cycle Analysis of Algae-Based Fuels with the GREET Model

Edward Frank, **Michael Wang**, Jeongwoo Han, Amgad Elgowainy, and Ignasi Palou-Rivera

Center for Transportation Research
Argonne National Laboratory

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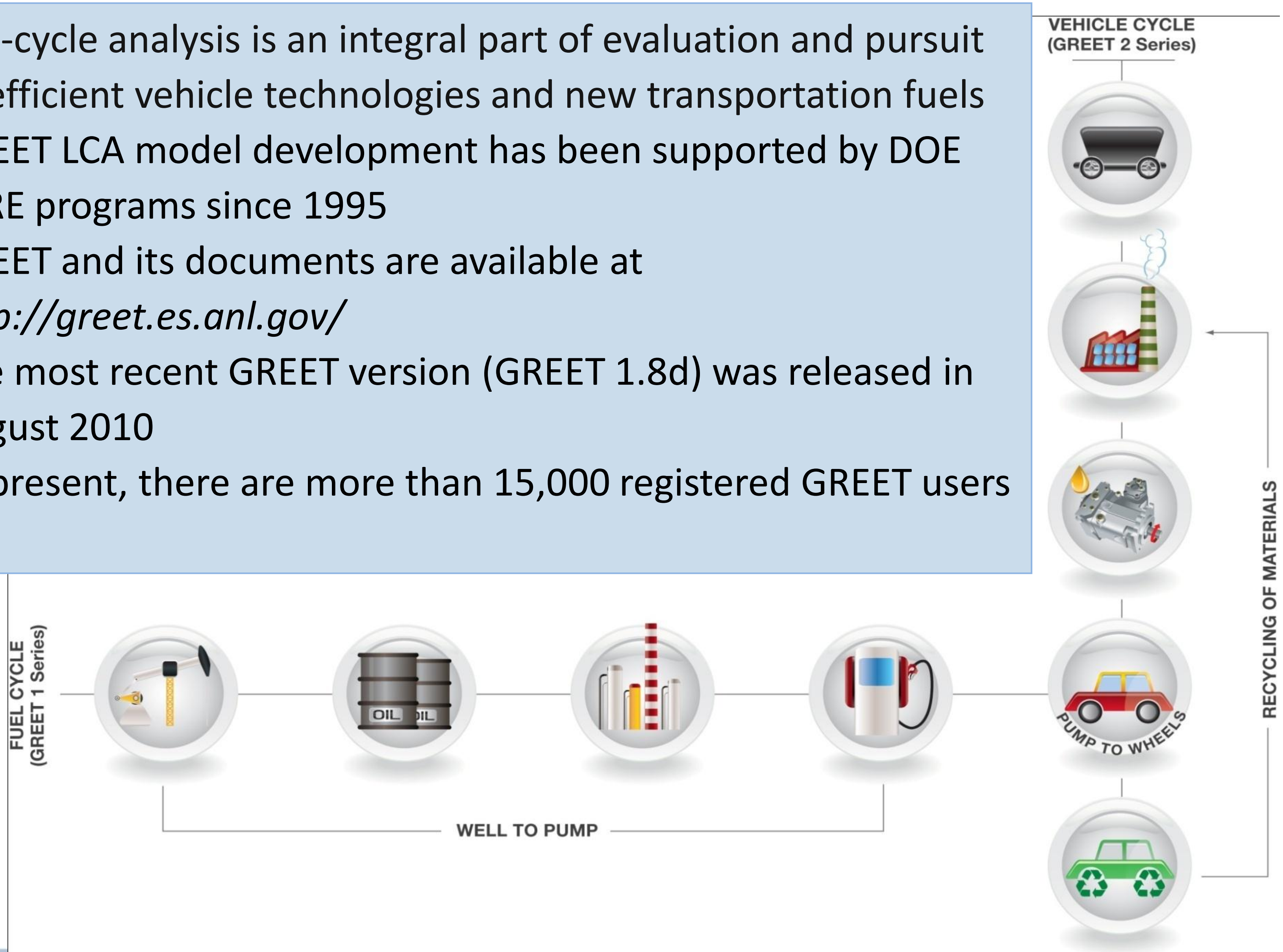
The GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) Model

- Life-cycle analysis is an integral part of evaluation and pursuit of efficient vehicle technologies and new transportation fuels
- GREET LCA model development has been supported by DOE EERE programs since 1995
- GREET and its documents are available at *http://greet.es.anl.gov/*
- The most recent GREET version (GREET 1.8d) was released in August 2010
- At present, there are more than 15,000 registered GREET users



The GREET Model Estimates Energy Use and Emissions of GHGs and Criteria Pollutants for Vehicle/Fuel Systems

- Energy use
  - Total energy: fossil energy and renewable energy
    - Fossil energy: petroleum, natural gas, and coal
    - Renewable energy: biomass, nuclear energy, hydro-power, wind power, and solar energy
- Greenhouse gases (GHGs)
  - CO_2, CH_4, and N_2O
  - CO_2e of the three (with their global warming potentials)
- Criteria pollutants
  - VOC, CO, NO_x, PM_{10}, $PM_{2.5}$, and SO_x
  - They are estimated separately for
    - Total (emissions everywhere)
    - Urban (a subset of the total)

GREET Includes More Than 100 Fuel Production Pathways from Various Energy Feedstocks

Feedstocks	Fuels
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 Forest 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.

GREET Includes Many Biofuel Production Pathways

- Ethanol via fermentation from
  - Corn
  - Sugarcane
  - Cellulosic biomass
    - Crop residues
    - Dedicated energy crops
    - Forest residues

- Renewable natural gas from
  - Landfill gas
  - Anaerobic digestion of animal wastes

- Corn to butanol

- Soybeans to
  - Biodiesel
  - Renewable diesel
  - Renewable gasoline
  - Renewable jet fuel

- Cellulosic biomass via gasification to
  - Fischer-Tropsch diesel
  - Fischer-Tropsch jet fuel

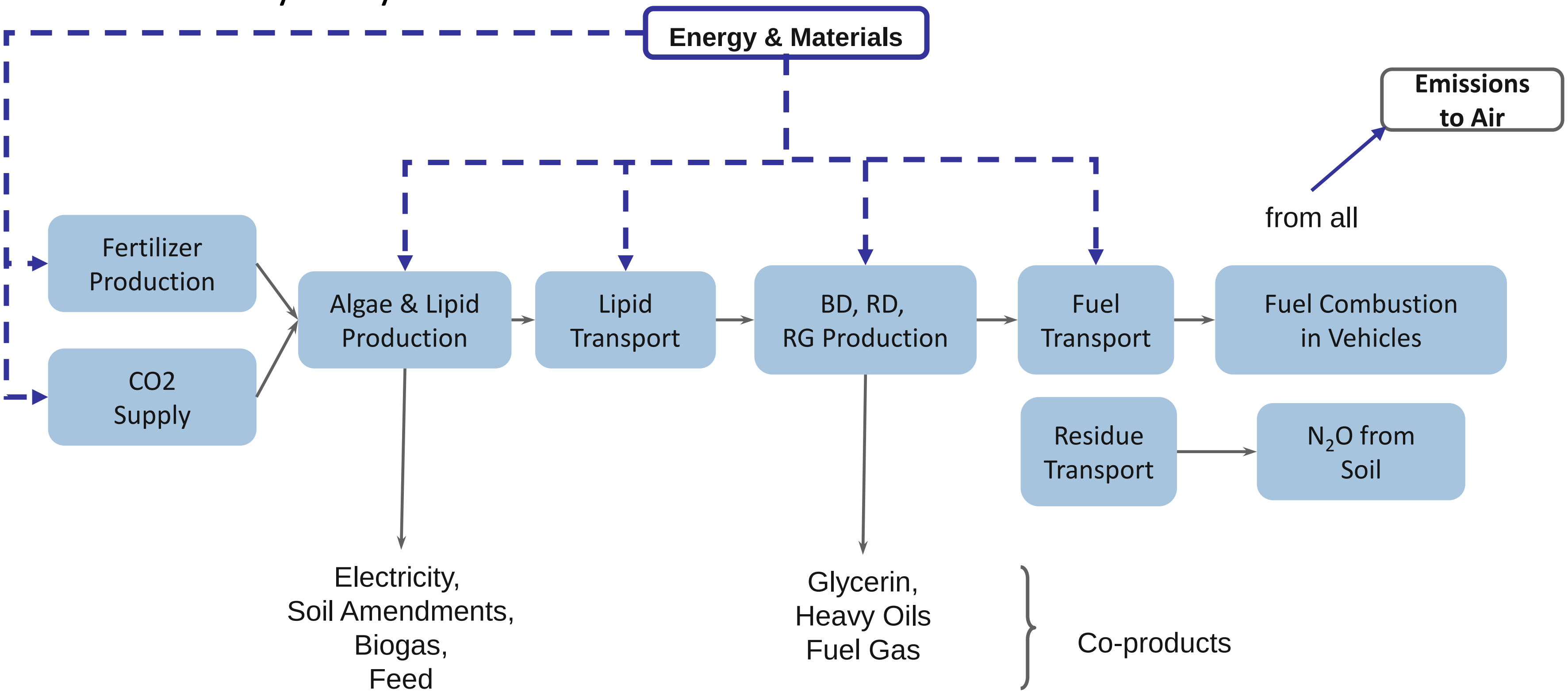
- Algae to
  - Biodiesel
  - Renewable diesel
  - Renewable gasoline
  - Renewable jet fuel

- Cellulosic biomass via pyrolysis to
  - Gasoline
  - Diesel

Algae LCA and System Boundary

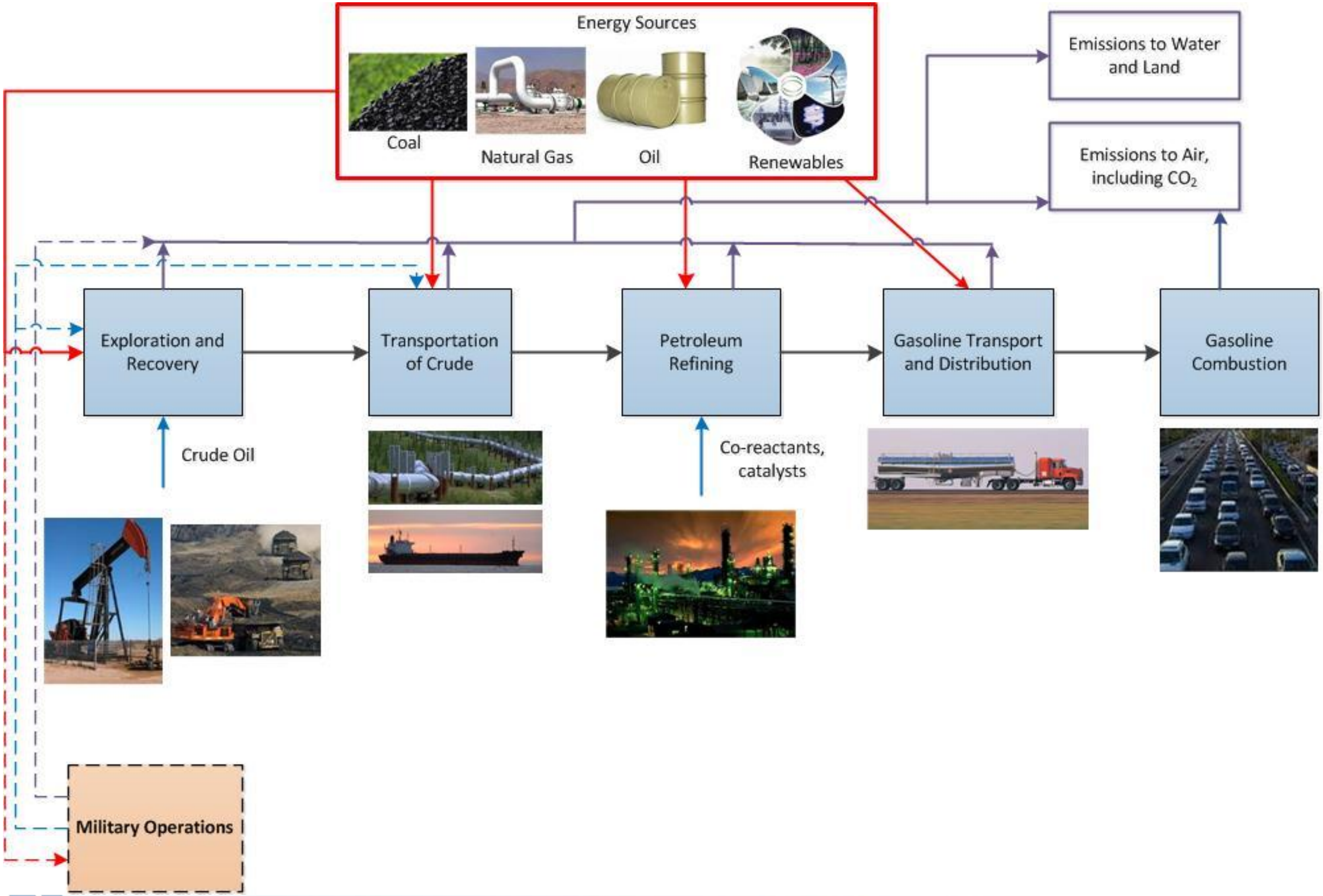
Goal of this work:

- Expand the GREET model for algae LCA to ensure comparability with LCAs of other biofuels and transportation fuels
- Identify key issues affecting algae LCA results, compare process options, facilitate algae community analyses



- Current LCA includes open pond systems only
- System boundary currently excludes infrastructure materials and land-use change

Life-Cycle Analysis System Boundary: Petroleum to Gasoline

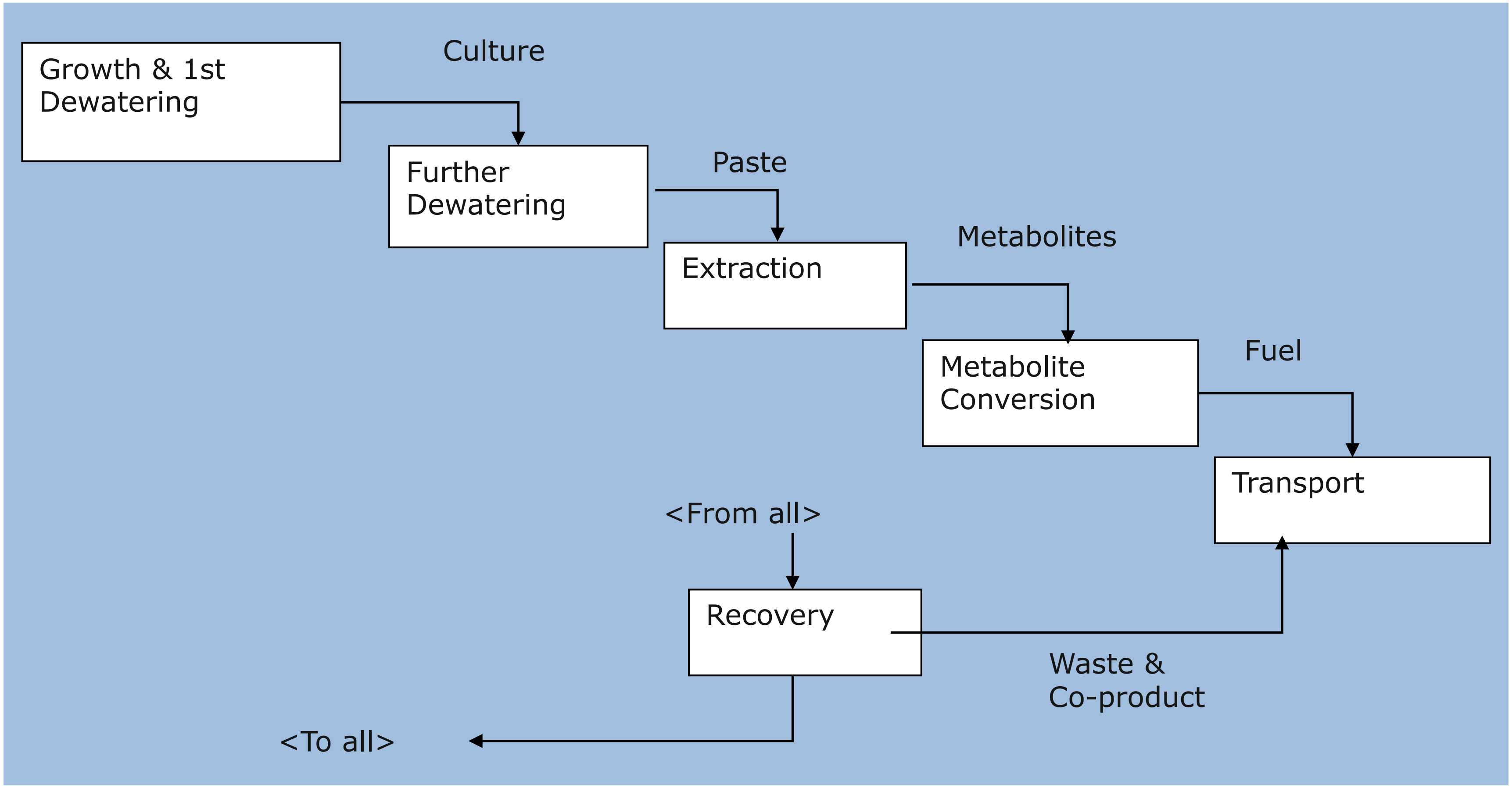


Approach: GREET Is Expanded with An Add-On Helper Tool - Algae Process Description (APD)

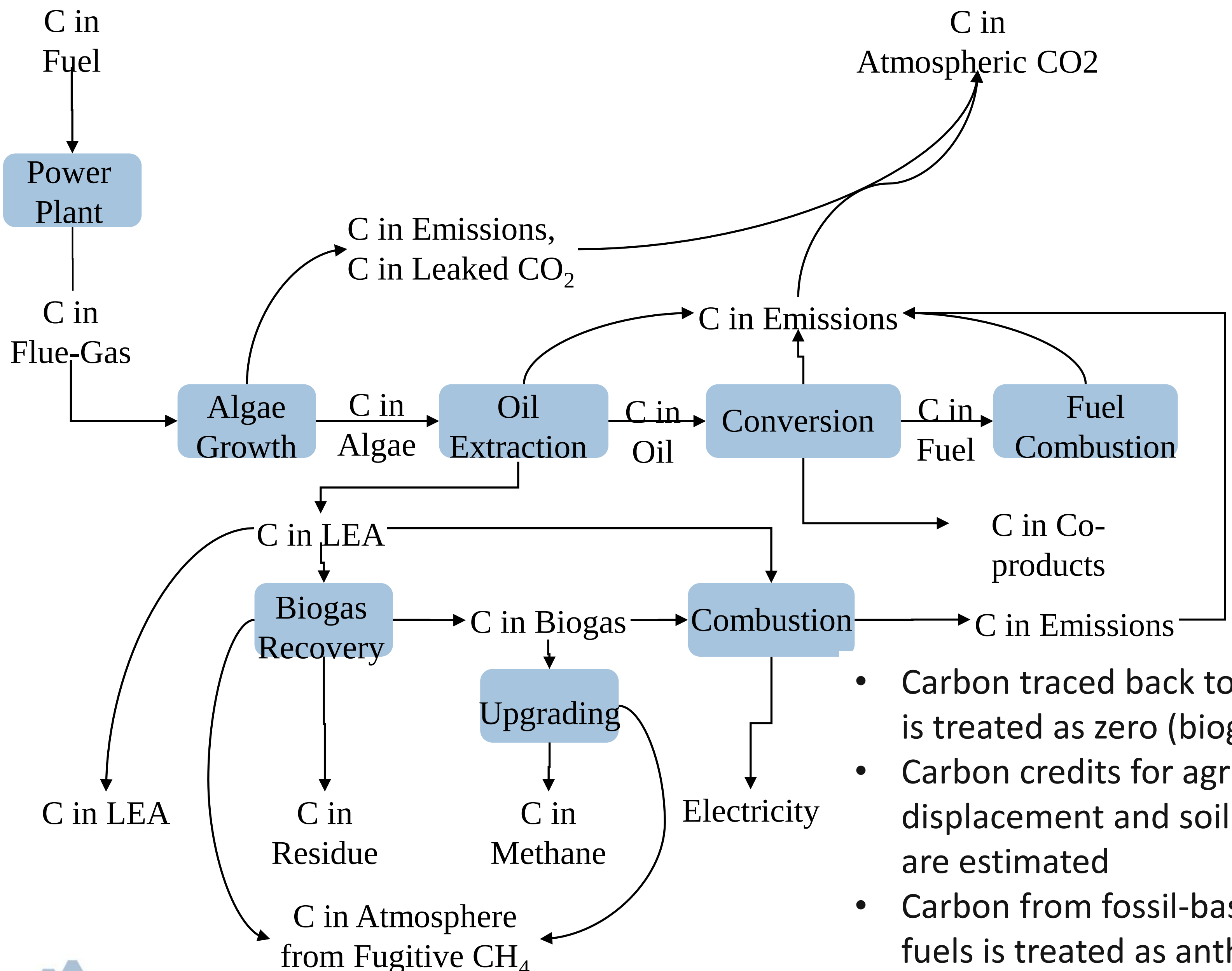
- Challenges for algae LCAs
  - Commercial pathways not yet defined: many scenarios
  - Lack of validated data, much proprietary
  - Published LCAs differ methodologically: hard to compare
- APD is intended to overcome some of these
  - Allows rapid definition of algae pathway from process inventory
  - Separates GREET from complexity of algae pathway definition
  - New processes easy to add: simple interface for users
  - Assembles model and passes back to GREET for LCA

Pathway Abstraction in APD

- Organizes process inventory, accounting, and reporting
- Helps user know where to plug-in and set parameters

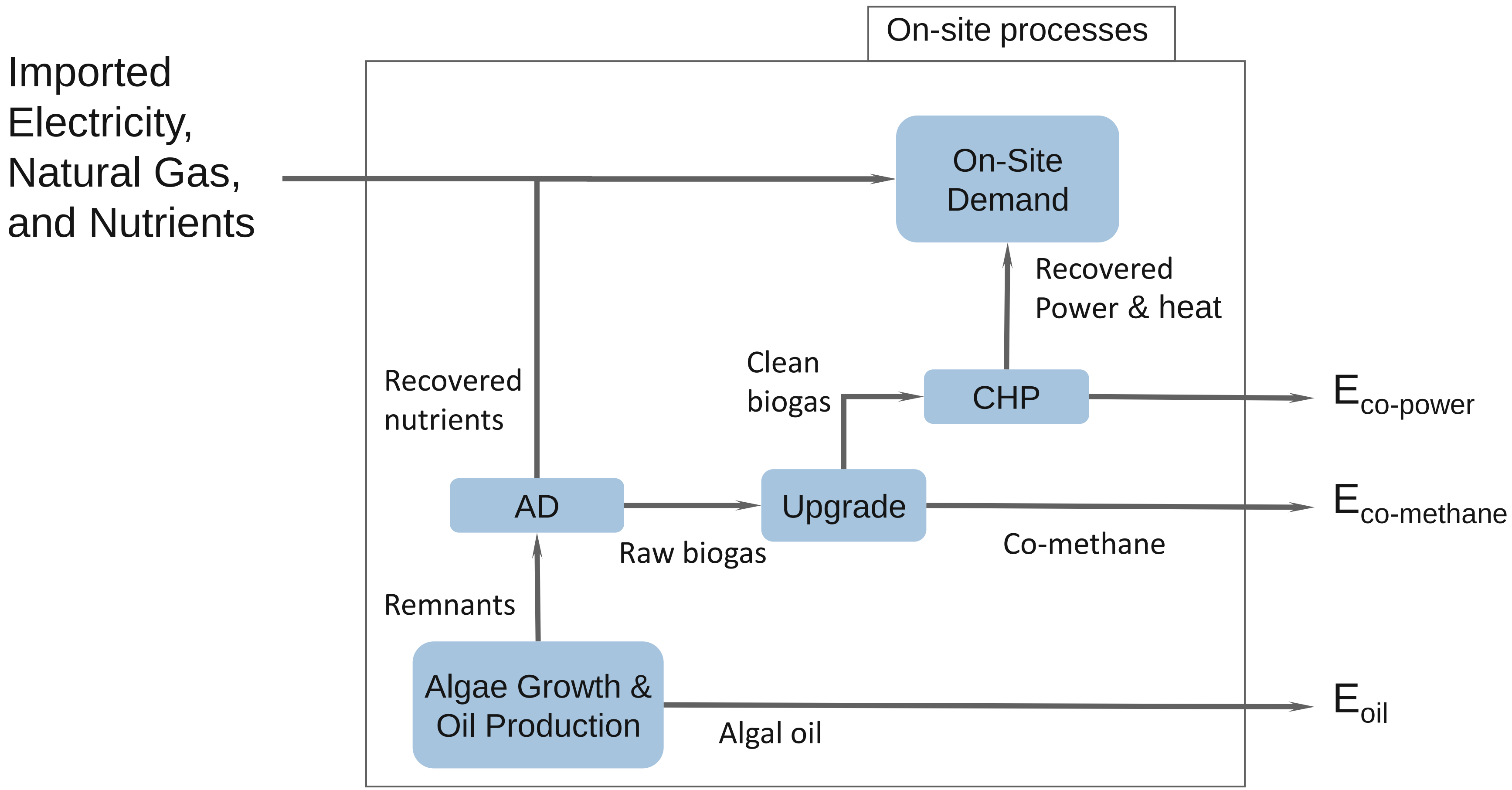


Algae LCA Carbon Accounting

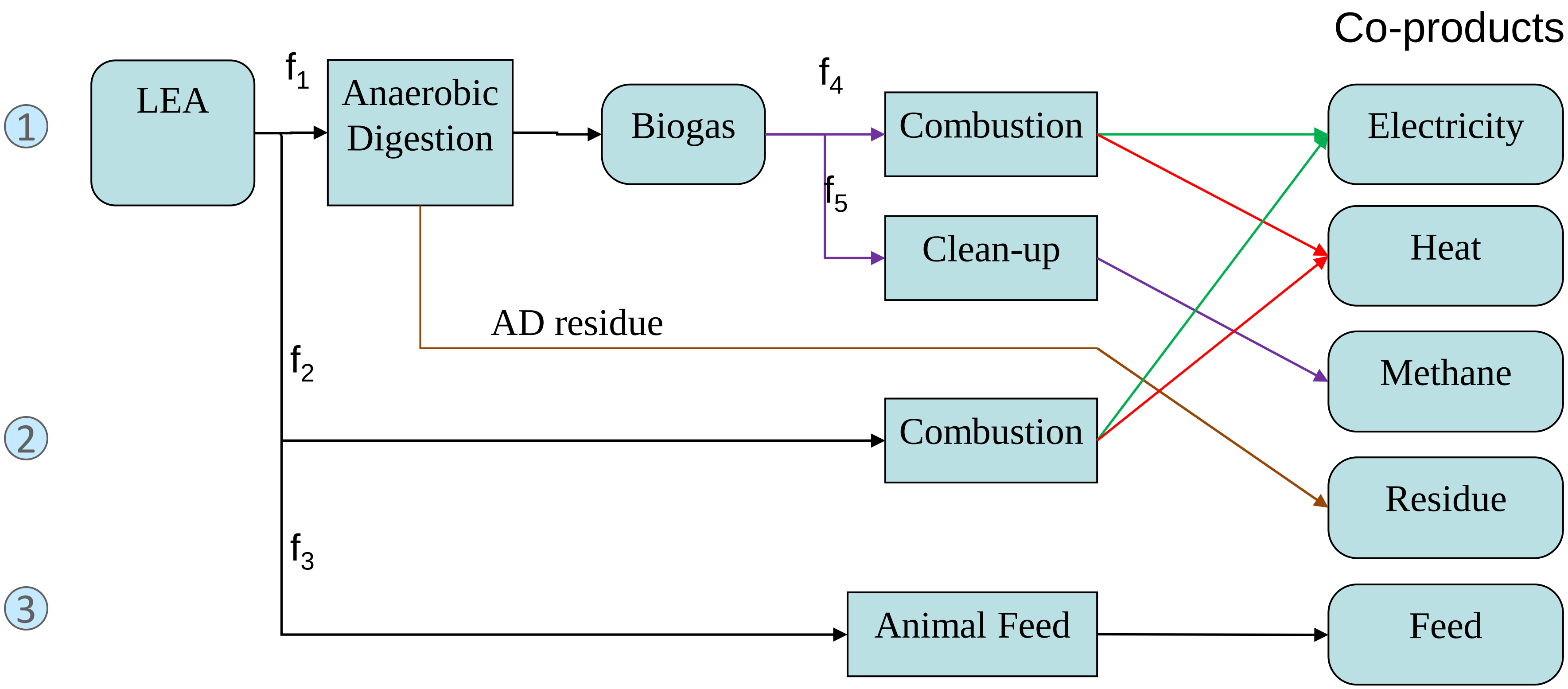


- Carbon traced back to power plants is treated as zero (biogenic)
- Carbon credits for agri. fertilizer displacement and soil amendments are estimated
- Carbon from fossil-based process fuels is treated as anthropogenic

Recovered Materials and Energy Reduce Internal Energy Demand

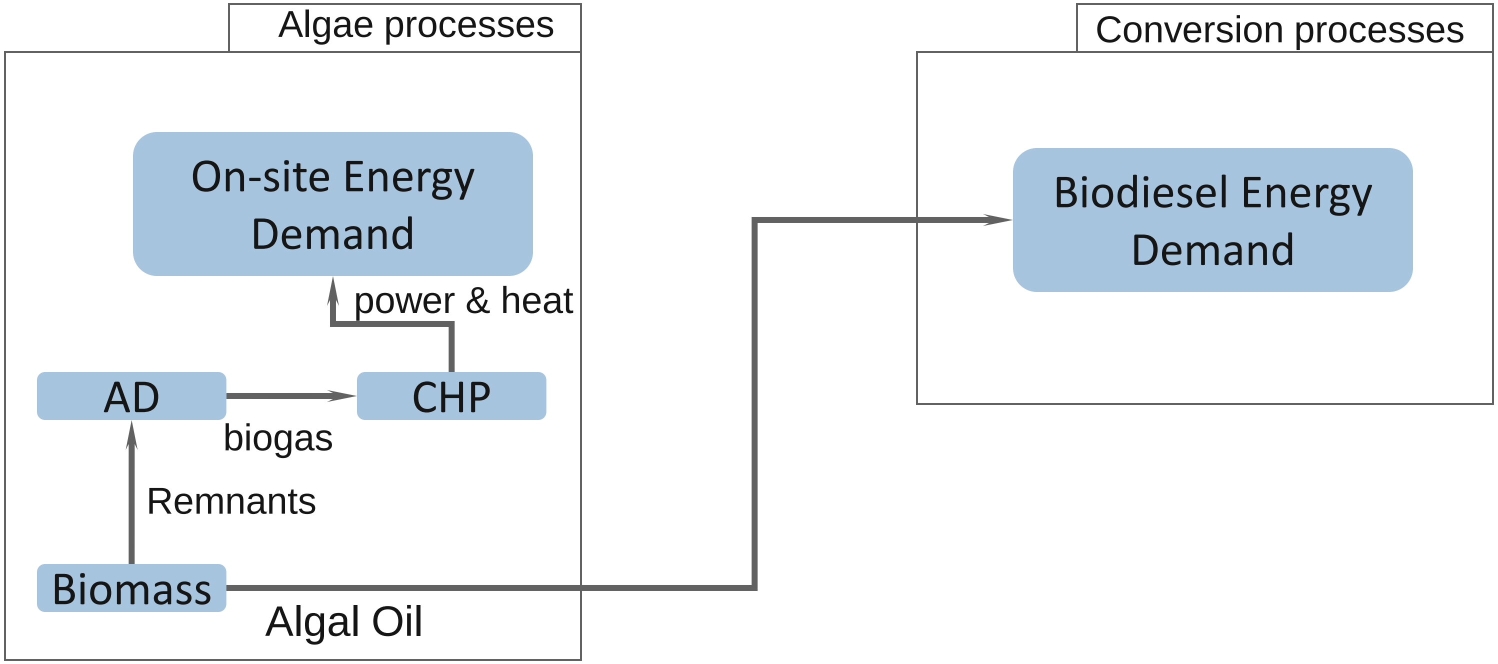


GREET: Co-Product Handling is a Key Issue



- ❑ Three Pathways Possible
- ❑ Five processes with co-products
- ❑ Five co-products from algae

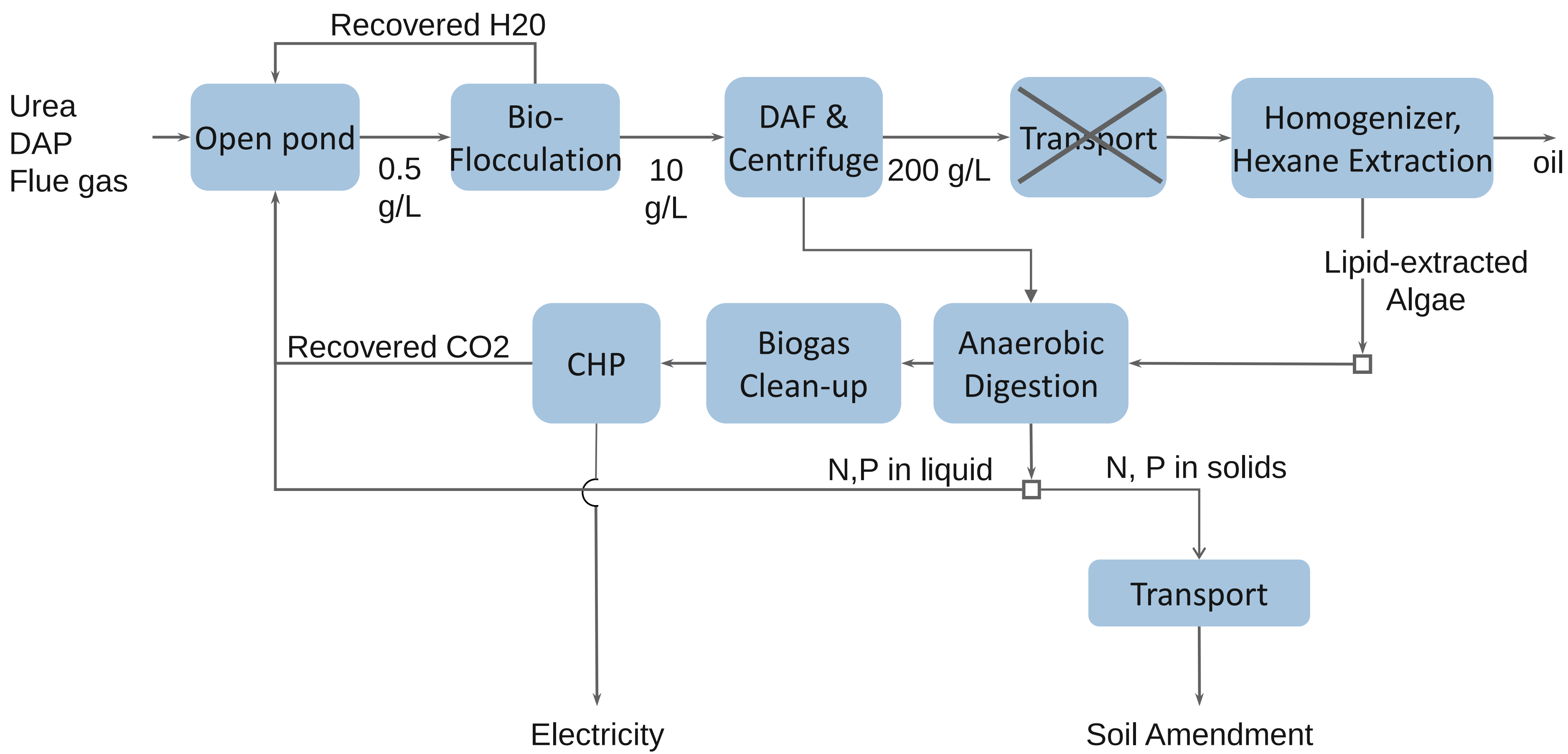
Net LCA Results Are Based on a Hybrid Approach



- Algae production and lipid-conversion allocation factors
  - $A_{algae} = E_{oil} / (E_{oil} + E_{co\text{-}power} + E_{co\text{-}methane})$
  - $A_{BD} = E_{BD} / (E_{BD} + E_{glycerin})$
- Sub-pathways combined with displacement method
  - $GHG_{Total, Allocated} = A_{BD}\ (A_{algae}\ (GHG_{algae} - GHG_{N,\ P2O5\text{-}displaced}) + GHG_{BD})$

Definition of Pathway Model for Baseline Scenario

Lipid Production Model - Baseline Scenario



Mixing Maintains Algal Suspension

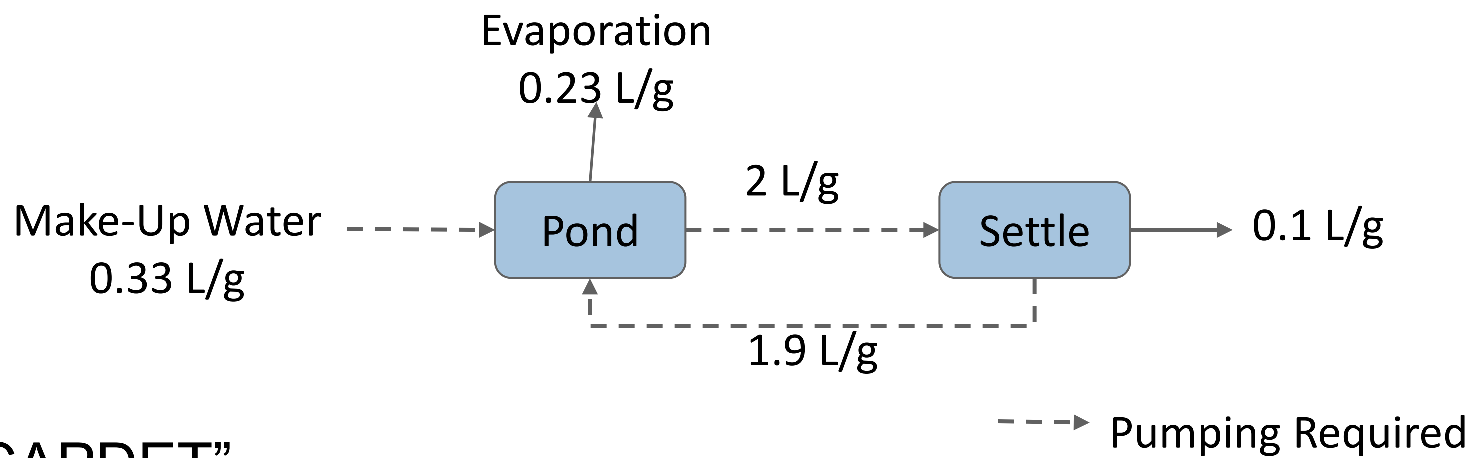
- Mixing power depends upon cube of mixing speed
  - Typically 15-30 cm/s, depending upon species

Source	W/ha	Speed, cm/s
Benemann 1996	1226	20
Stephenson, 2010	3670	30
Weissman, 1988	—	1 to 30 cm/s
Kadam, 2001	2344	
Lundquist, 2010	2000	25

- Baseline from Lundquist, then scale by v^3

Pumping Power Model

- Per gram of harvested algae
  - 2 L H_2O moves to settling then, 1.9 L <u>moves back</u>
  - 0.23 L additional water to replace evaporation
  - 4.23 L pumping per gram-algae



- "CAPDET"
  - A wastewater treatment simulator based upon Harris 1982
  - Intermediate water moved at ~15 ft total head
  - KWh/yr = 67,000 $Q^{0.9967}$, (Flow, Q, in million gallons/day)
  - Treat as good practice

Anaerobic Digestion CH_4 Yield is Estimated from Literature

Source	Feed	Digestable fraction	gVS/gTS	Theoretical CH_4 yield, L/g-VS	CH_4 Yield, L/g-VS	CH_4 Yield, L/g-TS	Digestion Time (d)
Ras 2010	*Chlorella*	33% of COD	0.85-0.90		0.15	0.15	16d
		51% of COD	0.85-0.90		0.24	0.22	28d
Samson 1982	*Spirulina*	66% of VS	0.89		0.26	0.23	33d, 70% CH_4
Sialve 2009	*Chlorella vulgaris*	46%[c] of VS		0.63-0.79	0.31-0.35	0.30[d]	64d
	Chlorella-scenedesmus sludge	36%[c] of VS		0.59-0.79	0.17-0.32	0.22	3-30d HRT
	Dunaliella salina	65%[c] of VS		0.68	0.44	0.40	28d
	Spirulina maxima	38%[c±] of VS		0.63-0.74	0.26	0.23	33d HRT
Collet 2011	*Chlorella*	56% of COD	0.90		0.29	0.26	46d, extrapolated from Ras.
Ehimen, 2011	*Chlorella*	25%-65% of VS	0.946		0.0-0.30	0.0-0.32	5-15d

Anaerobic Digestion Model

- Based on literature, the model uses:
  - 0.9 g-VS/g-TS
  - low, baseline, high = 0.2, 0.3, and 0.4 L CH_4/g-TS,
  - 67% CH_4 in biogas

- AD process energy (Collet, 2011)
  - 0.68 $KWh_{thermal}$/kg-TS
  - 0.14 $KWh_{electrical}$/kg-TS (includes solids separation)
  - Completely stirred mesophilic tank, 42d HRT, 5% TS

- Fugitive CH_4 emissions from AD
  - IPCC: 0-10%, "0" implied for good design
  - Flesch (2011): measured 3.1%
    - Loading, maintenance, and flaring
    - Fell to 1.7% when hopper was kept at negative pressure

There are Direct Emissions from Recovery

- Fugitive CH_4 from AD (continued)
  - Liebetrau (2010): Studied 10 biogas facilities in Germany
  - Several sources in plant ranged from 0.1% to 1.7% of total CH_4
  - Noted potential emissions from stored digestate

- Fugitive CH_4 from biogas clean-up
  - Clean-up removes particulates, sulfur, siloxanes, etc., and meets CHP input-pressure requirements
  - Pressure swing adsorption common: 2-13% CH_4 in off-gas
    - But off-gas can be processed.
  - Other processes less, e.g., LPCoob ~ 0.2%

- Baseline scenario uses 2% total CH_4 emissions, AD + clean-up

CHP - Combined Heat and Power via Turbine

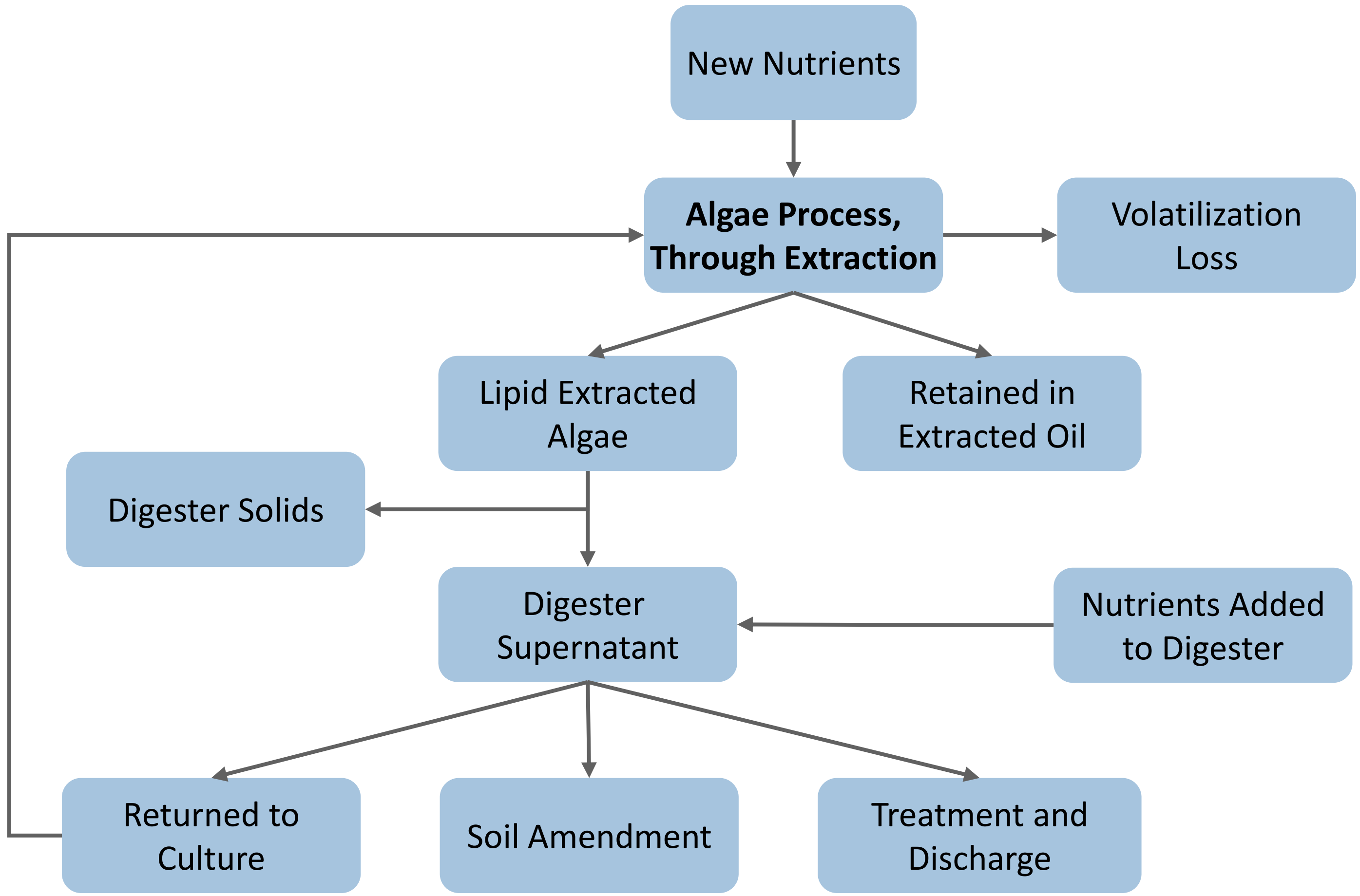
- 4,000 ha facility produces few x 10 $MW_{electrical}$

	Gas Turbine	Internal Combustion Engine
Electric efficiency	33%	37%
Heat recovery	70%	70%
NOx, g/mmBTU-in	113	**1,200**
CH_4, g/mmBTU-in	4.3	**369**

Efficiencies adapted from *Catalog of CHP Technologies*, EPA (2008)

- Model uses gas turbine (appropriate for this scale)
  - Recovered heat is used for hexane extraction and AD

Nutrient Flow in Algae Pathway



Nutrient Recovery

- ❑ Literature
  - ➢ Weissman and Goebel (1987)
    - N: 25% in sludge, 75% in liquid (inorganic)
    - P: 50% in sludge, 50% in liquid
    - 30% out-gassing if liquid returned to pond
  - ➢ Ras (2011): 68% of N in supernatant at 28d (Chlorella)
  - ➢ Collet (2001): Extrapolate Ras to 42d.
    - 90% N in supernatant, 5% volatilization (pH<7)

- ❑ This study:
  - ➢ 80% N in supernatant, 5% volatilization
    - ✓ 76% N to culture, 20% N to soil, of which 40% is bioavailable
  - ➢ Phosphorus
    - ✓ 50% to culture, 50% to soil

Algal Oil Extraction – Wet Hexane Extraction

- Theoretical process
- On-site rather than regional, since wet
- Energy consumption via previous modeling studies
  - Heat is obtained from CHP

Source	Process	NG, Wh/gm-oil	Electricity, Wh/gm-oil	Hexane, mg/gm-oil
Lardon				
Normal, dry	dry	1.9	0.4	11
Normal, wet	wet	0.6	2	16
Low-N, dry	dry	0.9	0.2	5.2
Low-N, wet	wet	2.8	1	7.4
Stephenson	wet	0.6	0.08	3
Lundquist, Large	dry	0.7	0.045	?
This study				
Baseline	wet	1.72	0.54	5.2
High	wet	3	1	10
Low	wet	0.5	0.1	2.5
Dry	dry	0.74	0.045	3

Details for the Baseline Scenario Model

Growth, Harvest, and Extraction

Raceway (pond) → 0.5 g/L → Flocc. & Settle → 10 g/L → DAF → 100 g/L → Centrifuge → 200 g/L → Homogenizer → Wet Hexane Extraction

Raceway (pond)
- 25 cm/s
- 48 kWh/ha/d
- 2.2 g-CO_2/g-algae
- (15% CO_2 loss)
- 1.5m sump
- 0.6 cm/day
- 25 g/m^2/d
- 25 wt% lipid
- 25 wt% protein
- 50 wt% carbohydrate
- C:N:P = 103 : 9.8 : 1
- 50 wt% carbon

DAF
- 90% effic.
- CAPDET
- 1.5e-4
- KWh/dry-g

Centrifuge
- 95% effic.
- 1 HP/gpm

Homogenizer
- 90% effic.
- 25 kWh/dry-ton
- EPA/Davis/GEA
- Niro Soavi

Wet Hexane Extraction
- 95% effic.

Recovery

Anaerobic Digestion → biogas → CHP

Anaerobic Digestion
- 0.3 L/g-TS
- 67% CH_4

CHP
- 33% Elect.
- 76% Total

g/g-algae

	N	P
New	0.014	0.0063
Recovered	0.042	0.0063

Results for Baseline Scenario

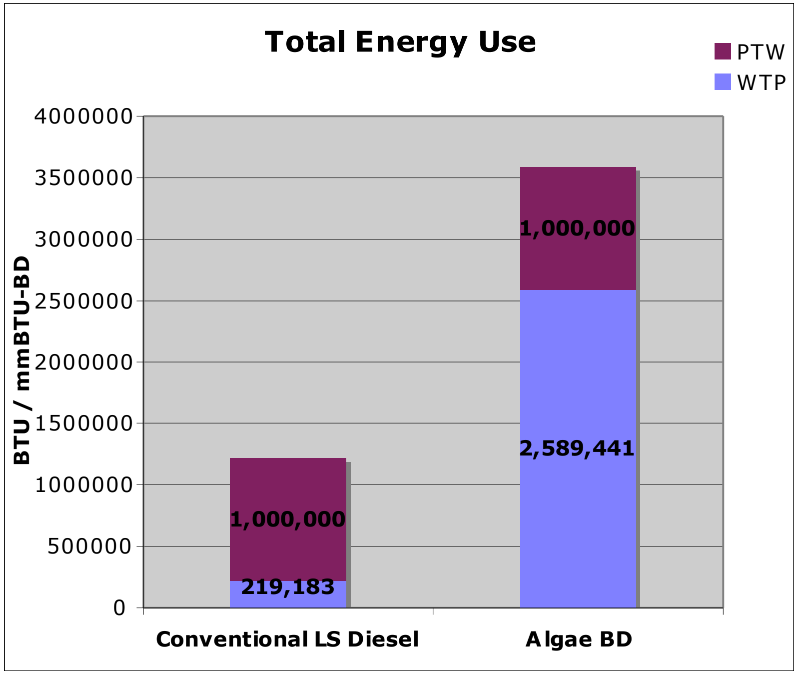
Aggregated Energy and CO2 Balance

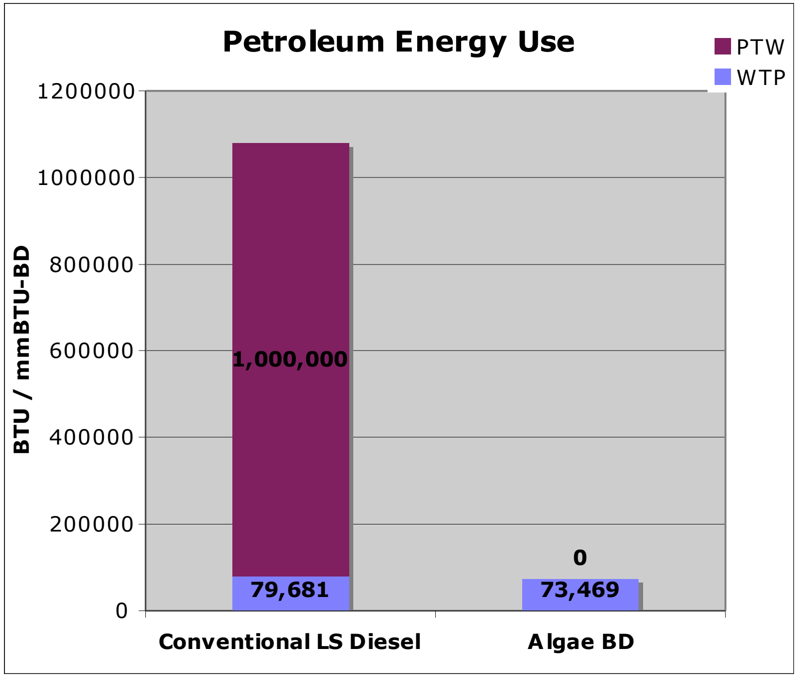
CHP Electricity	Btu / Btu-BD
Total on-site generation	0.387
Total on-site demand	0.514
Deficit Imported	0.128

CHP Heat	Btu / Btu-BD
Total on-site generation	0.500
Total on-site demand	0.344
Discarded heat	0.156

CO_2	kg / mmBtu-BD
Total recovered on-site	92
Total on-site demand	323
Deficit imported	231

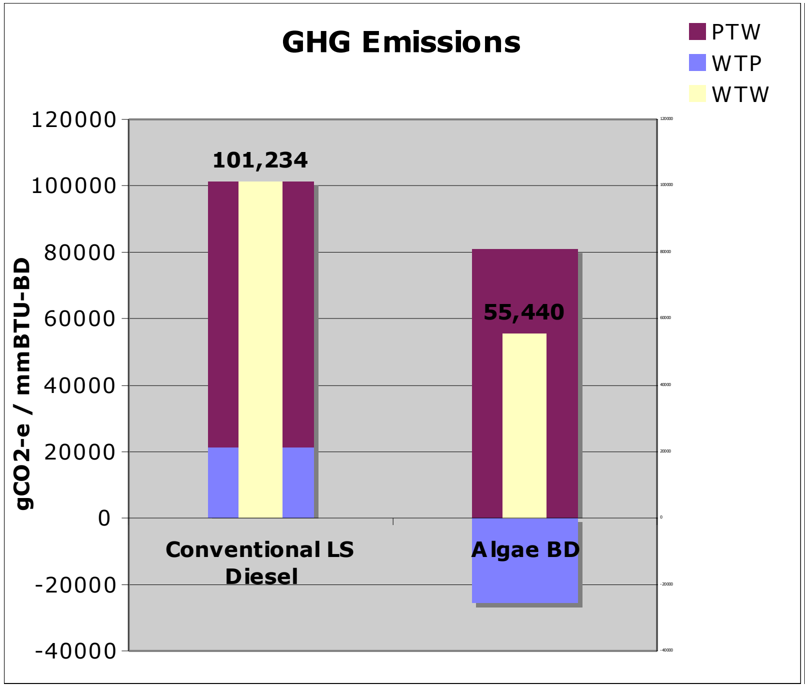
Total Energy and Petroleum Energy Use Results

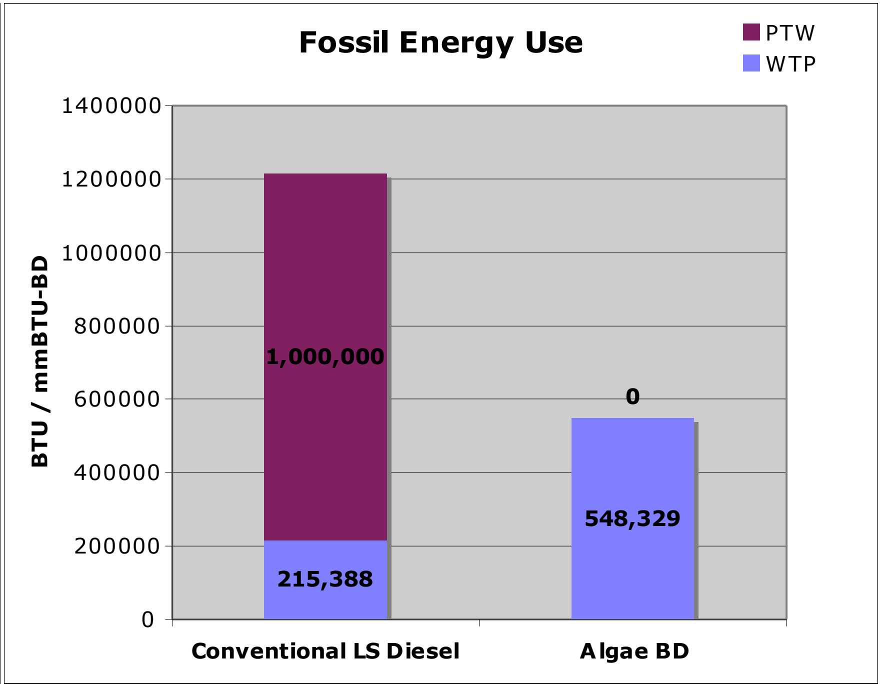




Total energy use includes renewable energy in the biomass as well as fossil energy.

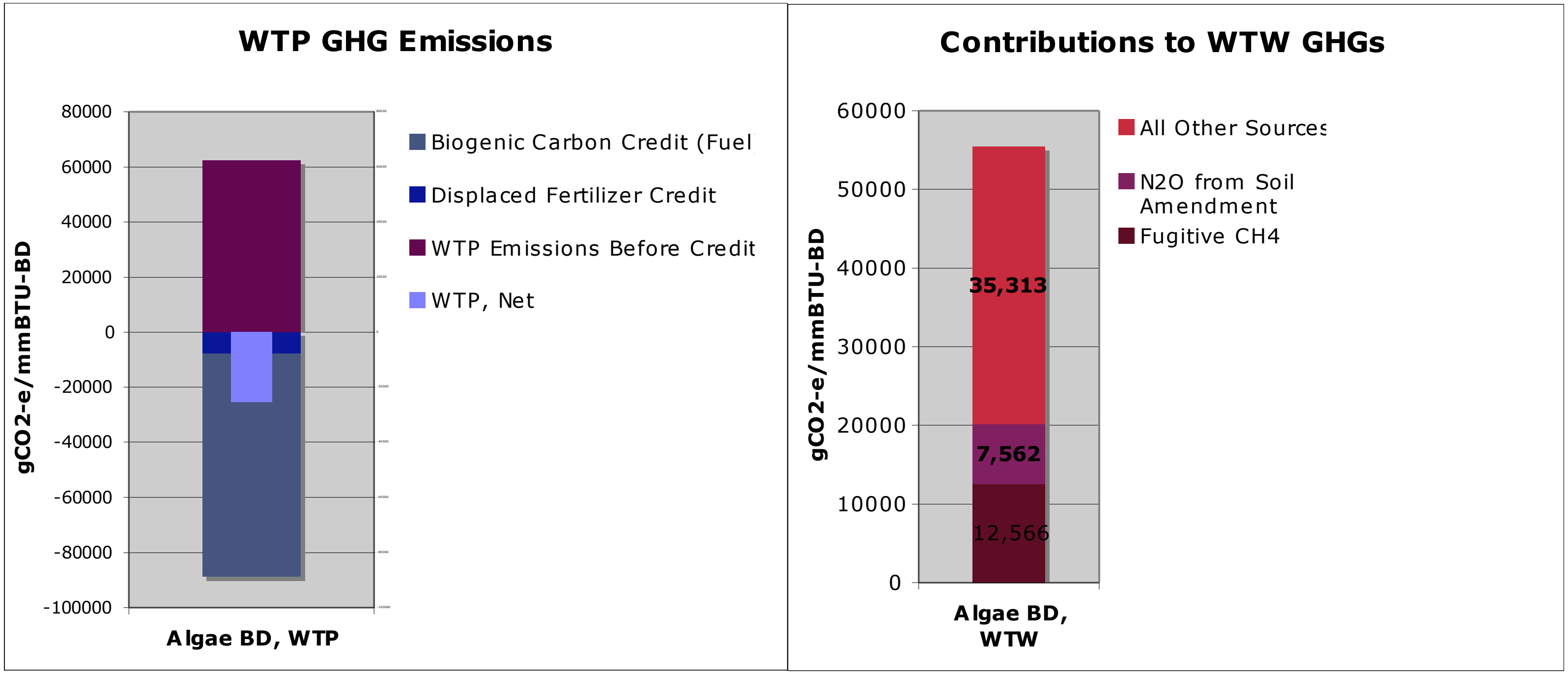
Fossil Energy and GHG Results





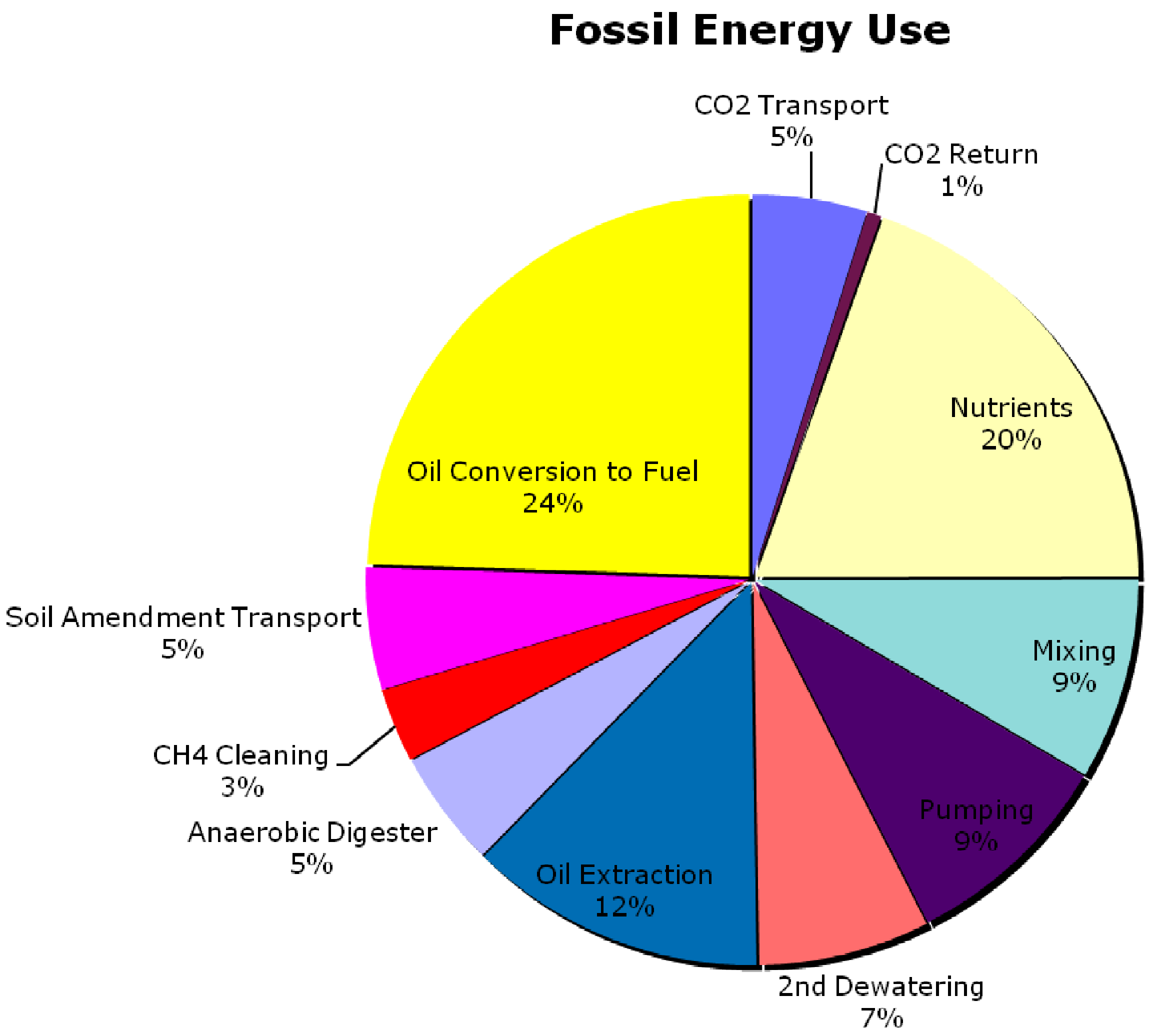
- ❑ Baseline scenario has significant GHG reduction
- ❑ Accurate treatment of recovery (AD, CHP) is essential
  - ➢ 128,000 BTU-electricity imported (fossil) per mmBTU of biofuel
  - ➢ Would be 514,000 BTU-electricity without AD recovery
  - ➢ 76% of N and 100% of P recovered

Breakdowns of GHG Emissions



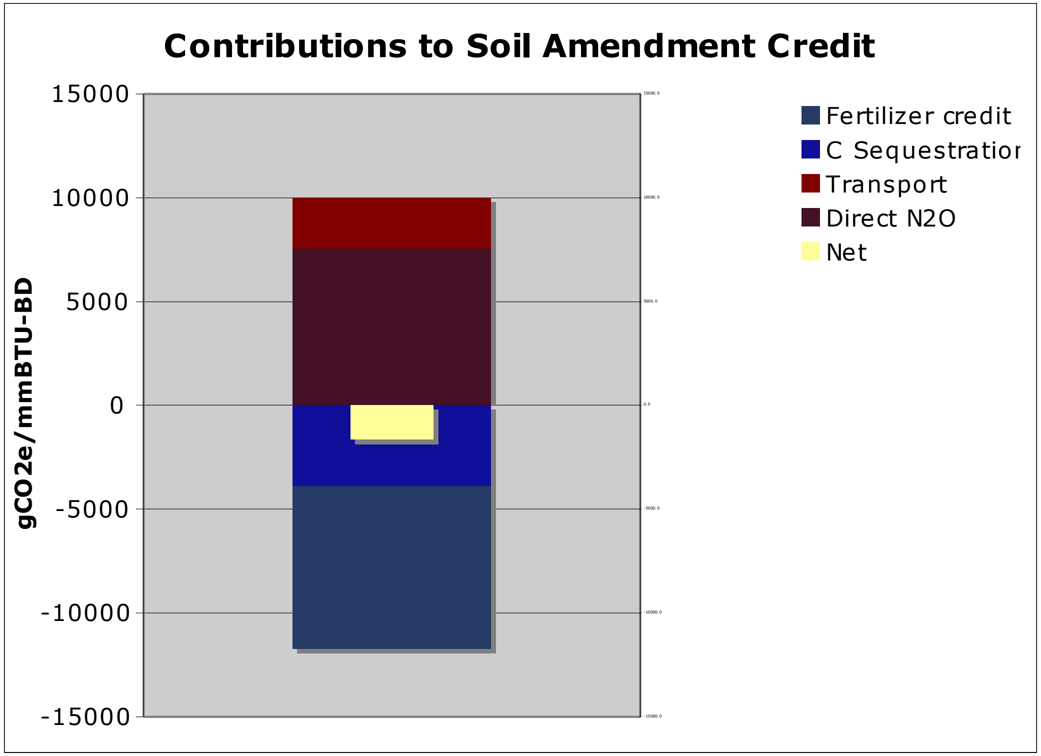
- ❑ Biogenic credit cancels substantial emissions from growth and processing
- ❑ Substantial direct CH_4 from AD + biogas clean-up
  - ➢ Technology choice, operations and maintenance are important
  - ➢ Beware of shortcuts for CAPEX, OPEX reduction here
- ❑ Also, significant amount of N2O emissions from AD residues in AD sites and farming fields

Breakdowns of Fossil Energy Use



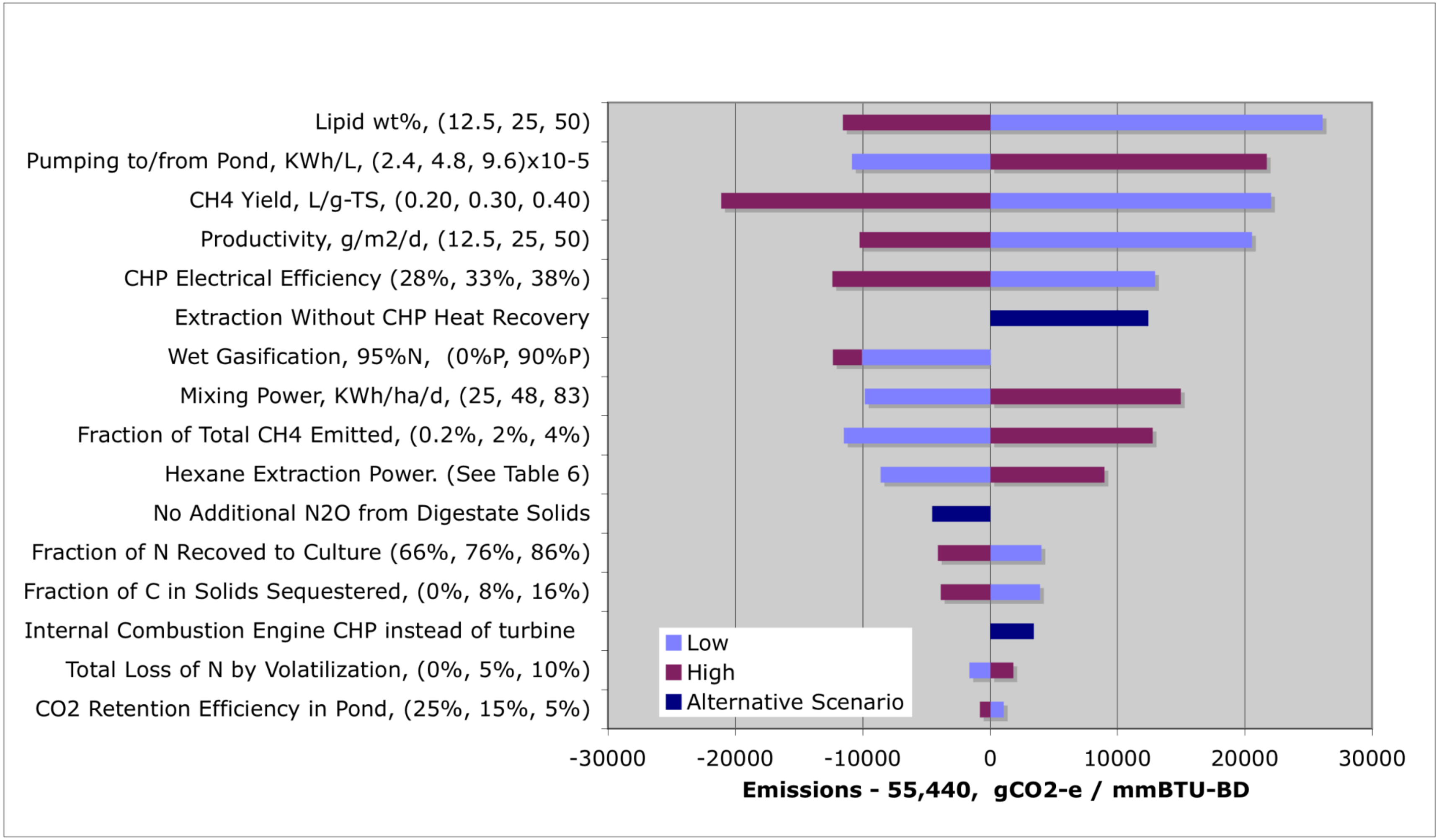
Breakdowns are before a fertilizer credit of 55,500 BTU/mmBTU-BD for farming land application of AD residues.

GHG Credits from AD Solids as Fertilizer Replacements



Credit from applying AD digestate solids (residue) to soil as a fertilizer is largely canceled by transport and N_2O emissions in the field; understanding N_2O emission factor is important

GHG Emissions Sensitivity Analysis



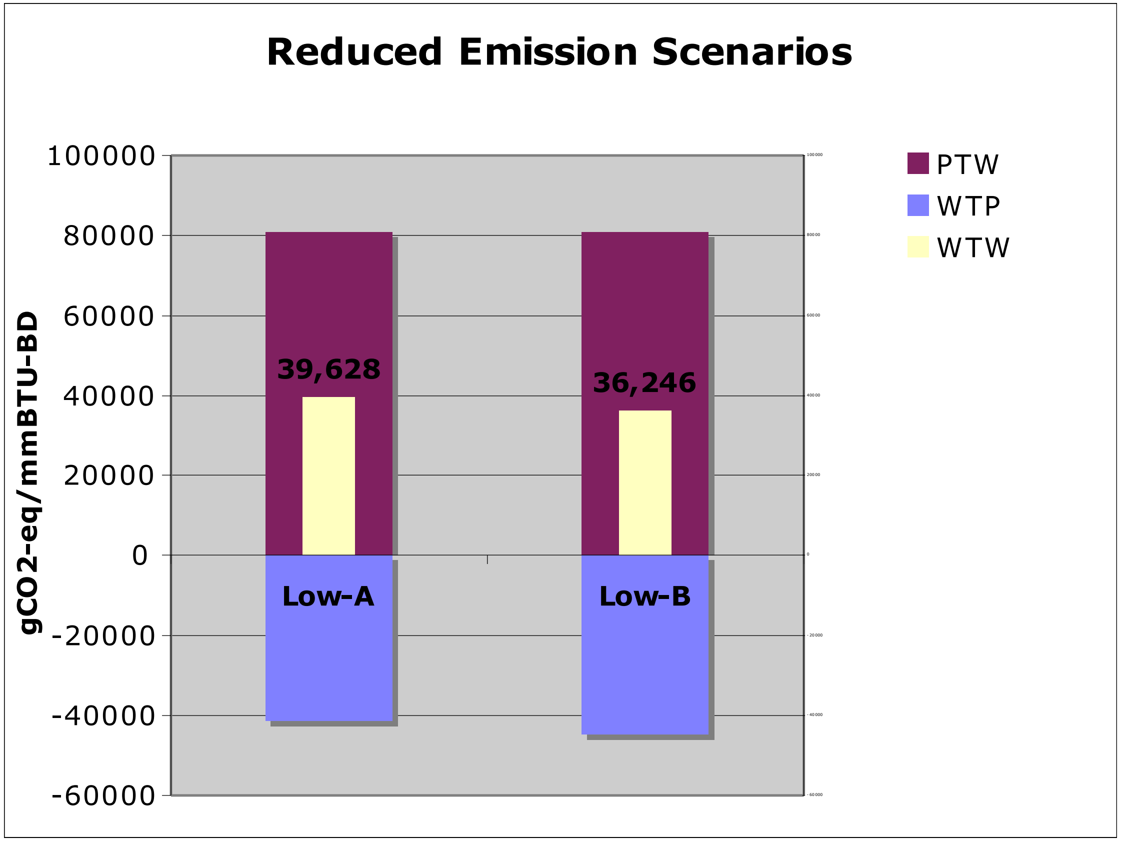
- Confidence interval <u>not</u> uniform parameter to parameter
  - Not fair comparison but does show ($dG/dx \bullet \Delta x$) for Δx shown

Reduced Emissions Scenarios

- Low-A
  - Increase lipid fraction from 25 wt% to 35 wt%
  - Replace AD with catlytic hydrothermal gasification
    - 95% N recovery and 90% P recovery
  - Total fugitive CH_4 emissions reduced from 2% to 0.2%
  - Reduce CHP efficiency from 33% to 29%
  - Reduce DAF performance from 10 wt% solids output to 8 wt%
  - Reduce C-sequestration to zero

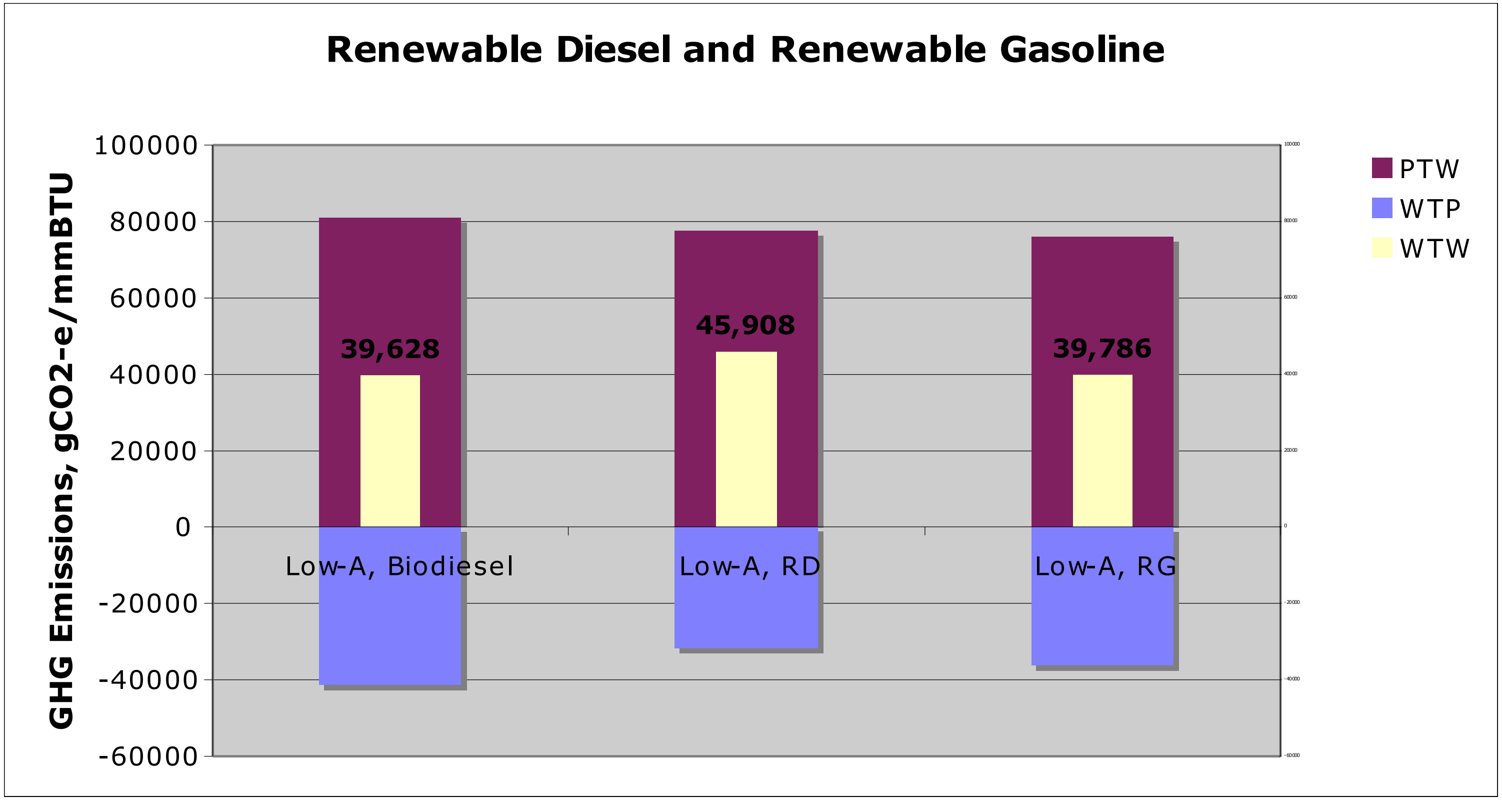
- Low-B
  - Increase lipid fraction from 25 wt% to 35 wt%
  - Productivity increased from 25 $g/m^2/d$ to 30 $g/m^2/d$
  - Total fugitive CH_4 emissions reduced from 2% to 0.2%
  - Hexane extraction energy demand is reduced by 41% from baseline scenario
  - Reduce C-sequestration to zero

GHGs For Reduced Emission Scenarios

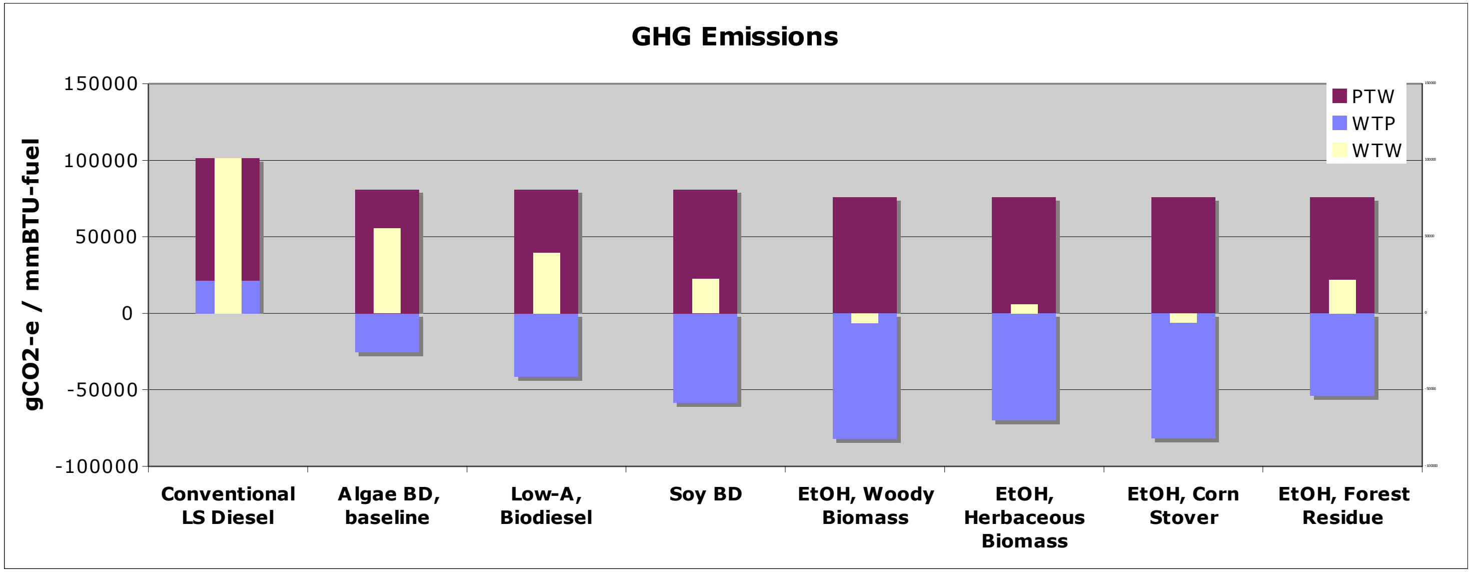


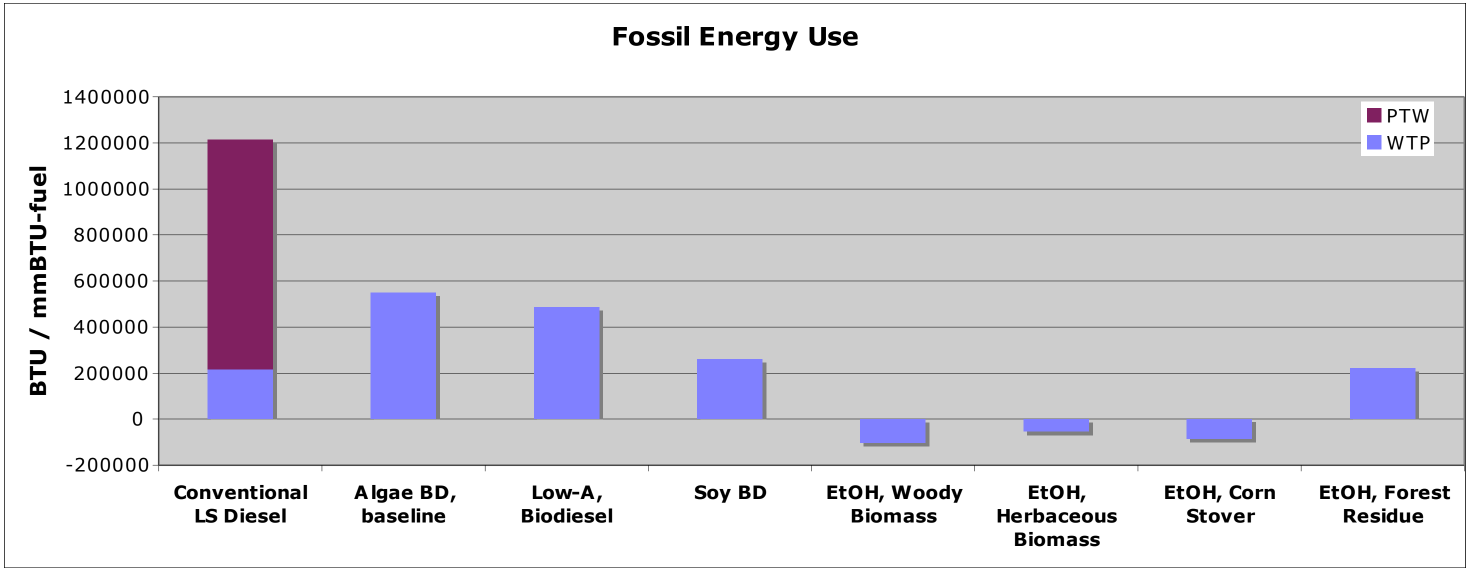
Baseline scenario had 55,440 gCO_2e/mmBTU-BD

Renewable Diesel and Renewable Gasoline Have Similar GHGs Because of Energy Allocation



Energy and GHG Results: Algae vs. Other Fuels





Conclusions

- GHG emission reductions may vary from less than 50% to more than 60%, relative to that of low-sulfur petroleum diesel
  - Baseline scenario results in 45% reduction
  - Two low-emission scenarios result in 61-64% reductions
- Total fossil energy appears to be high vs. other biofuels
- Cautionary notes to current results
  - Based, in part, upon undemonstrated processes and performances
  - Flue-gas CO_2 was treated as atmospheric
- Key outstanding issues
  - Electricity and nutrient recovery from residuals is essential but could be a substantial source of emissions
    - Fugitive CH_4 from AD and from biogas clean-up
    - N_2O from digestate-solids applied to fields
  - Pumping between unit operations risks significant GHG burden
    - Careful consideration of site layout required
    - Tradeoff between distance (centralization), solids content, and power
    - Footprint vs. required head
- Opportunity: improvements, required for economic viability and under intensive R&D, could reduce GHGs and fossil energy further

Acknowledgment

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A technical report from which this presentation is based on will be available at the GREET website in days (http://greet.es.anl.gov/)

Contacts

Dr. Ed Frank: efrank@anl.gov
Dr. Michael Wang: mqwang@anl.gov