Biofuel Life-Cycle Analysis With the GREET Model

Michael Wang

Center for Transportation Research

Argonne National Laboratory

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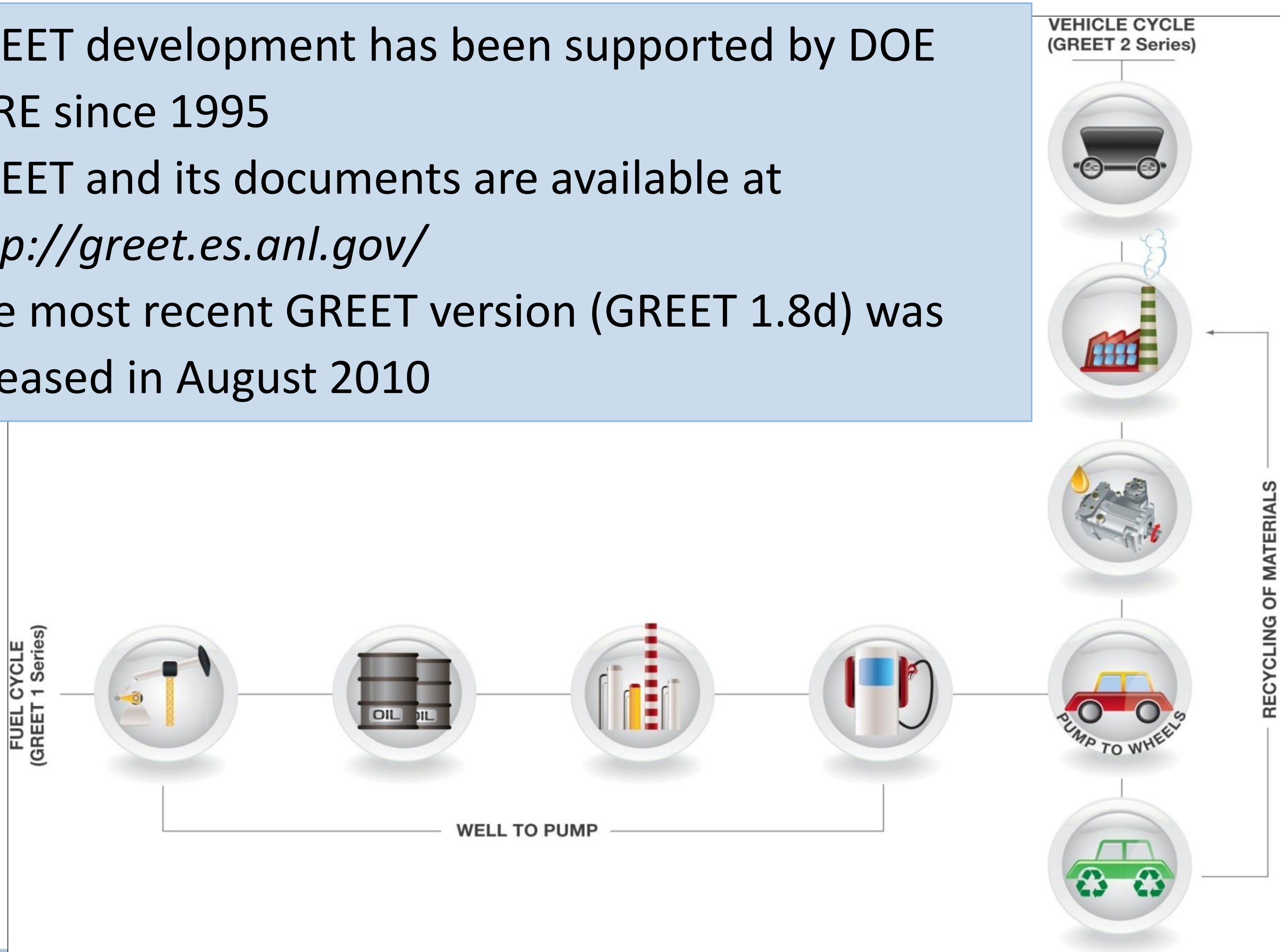
The GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) Model

- GREET development has been supported by DOE EERE 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



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}, $PM_{2.5}$, SO_x
  - They are estimated separately for
    - Total (emissions everywhere)
    - Urban (a subset of the total)

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

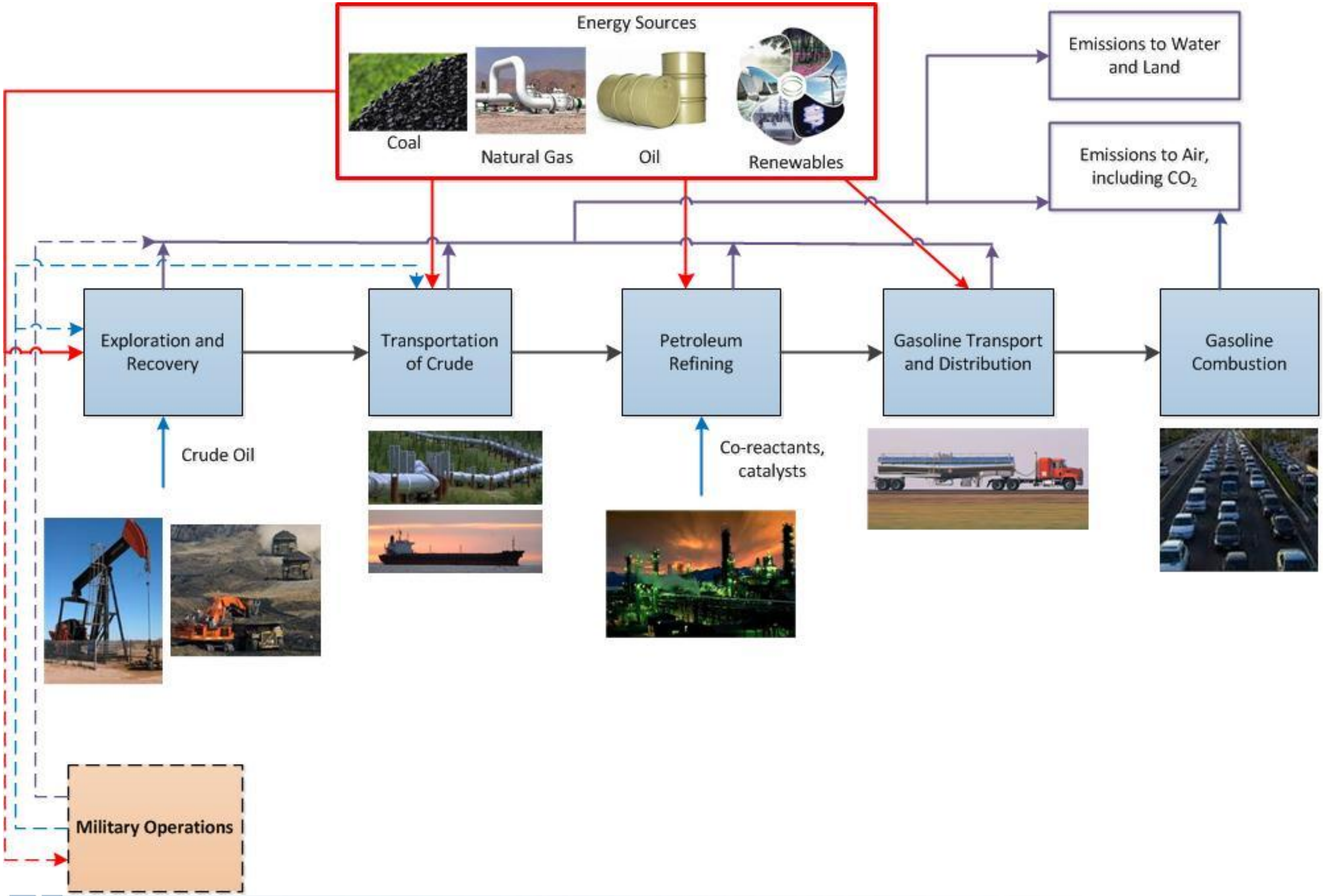
- Soybeans to
  - Biodiesel
  - Renewable diesel
  - Renewable gasoline
  - Renewable jet fuel

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

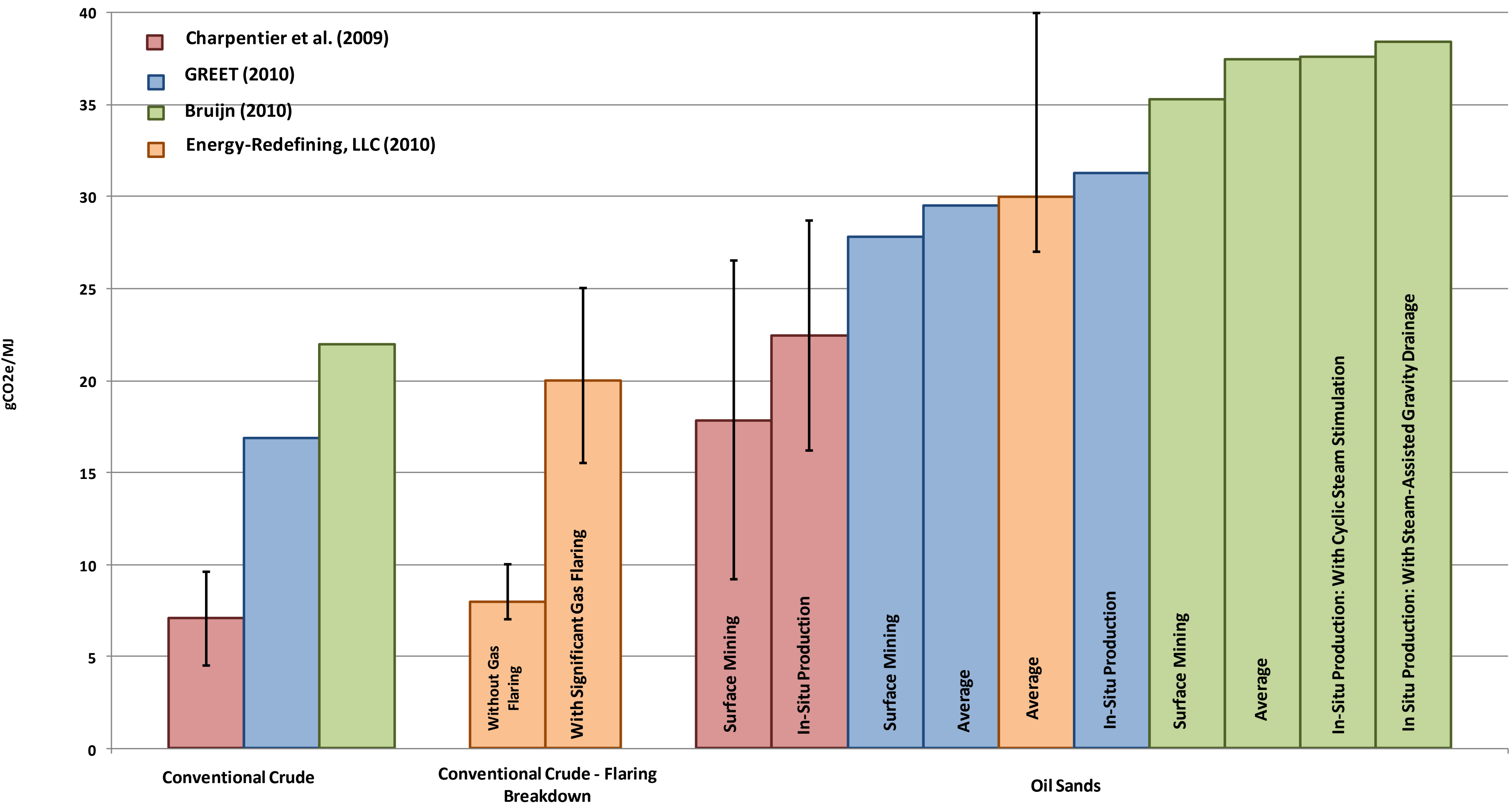
- Algae to
  - Biodiesel
  - Renewable diesel
  - Renewable gasoline
  - Renewable jet fuel

- Cellulosic biomass via pyrolysis to
  - Gasoline
  - Diesel

Life-Cycle Analysis System Boundary: Petroleum to Gasoline

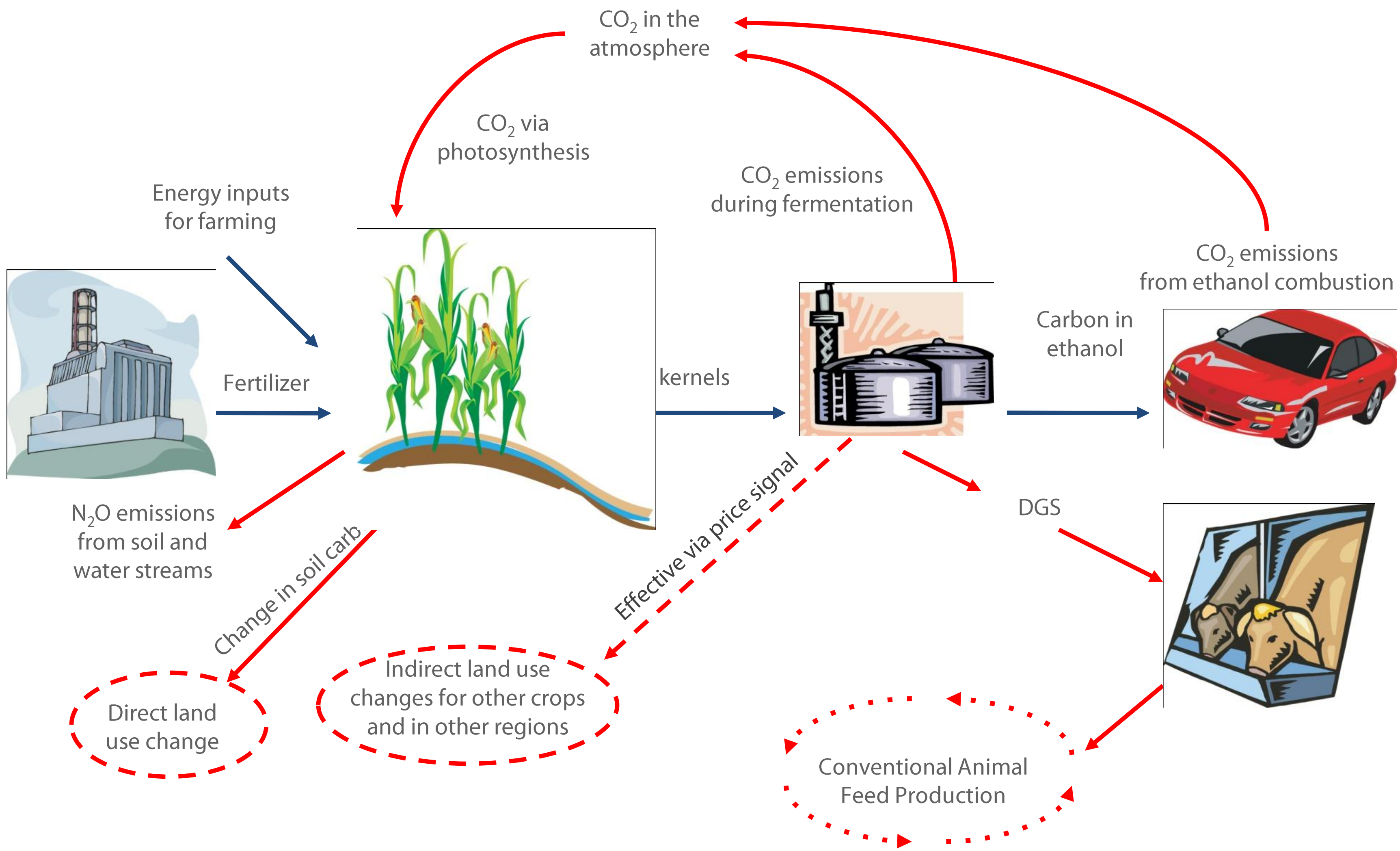


Well-to-Pump GHG Emissions of Petroleum Gasoline

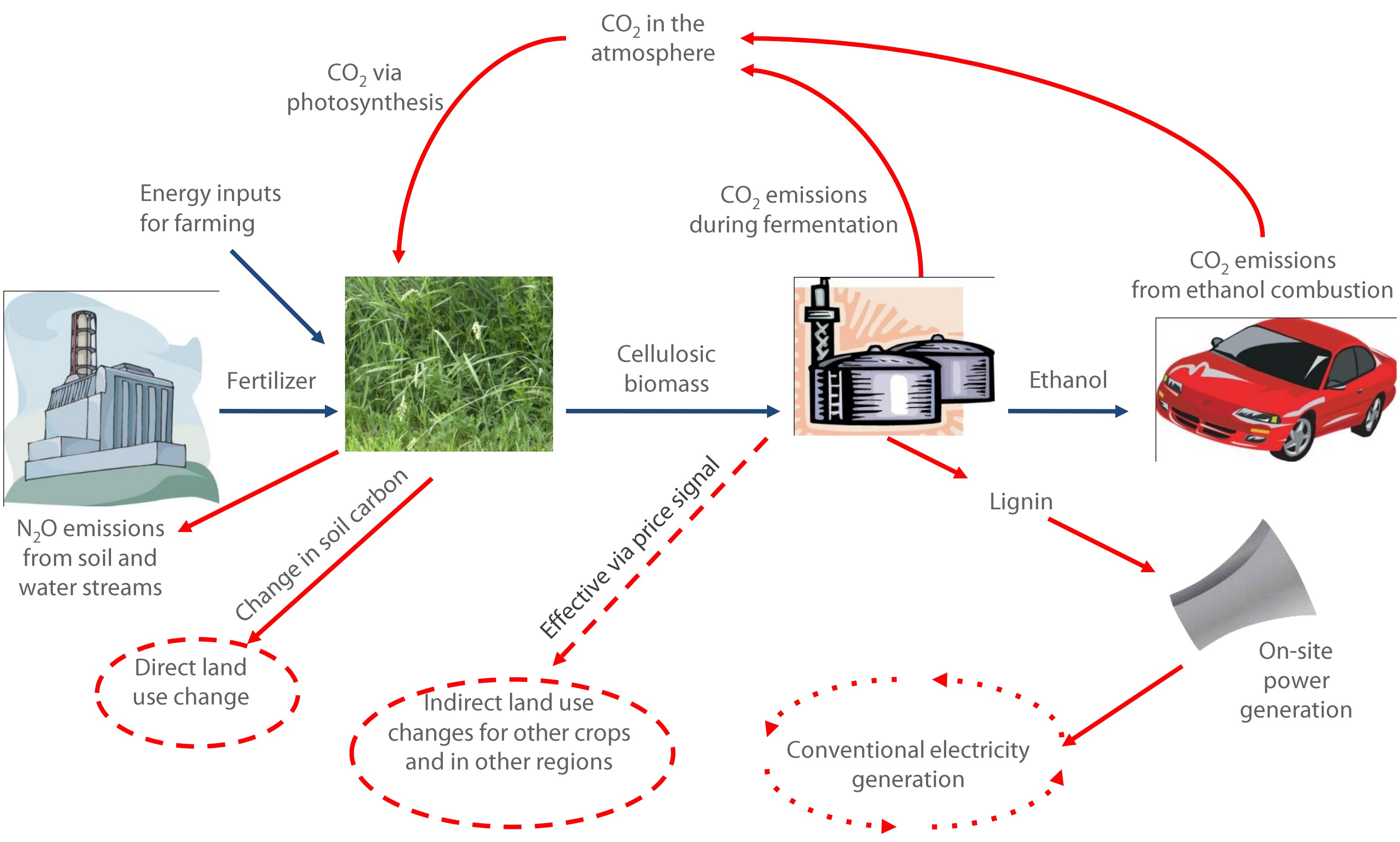


Gasoline combustion: about 75 g/MJ GHG emissions

Life-Cycle Analysis System Boundary: Corn to Ethanol



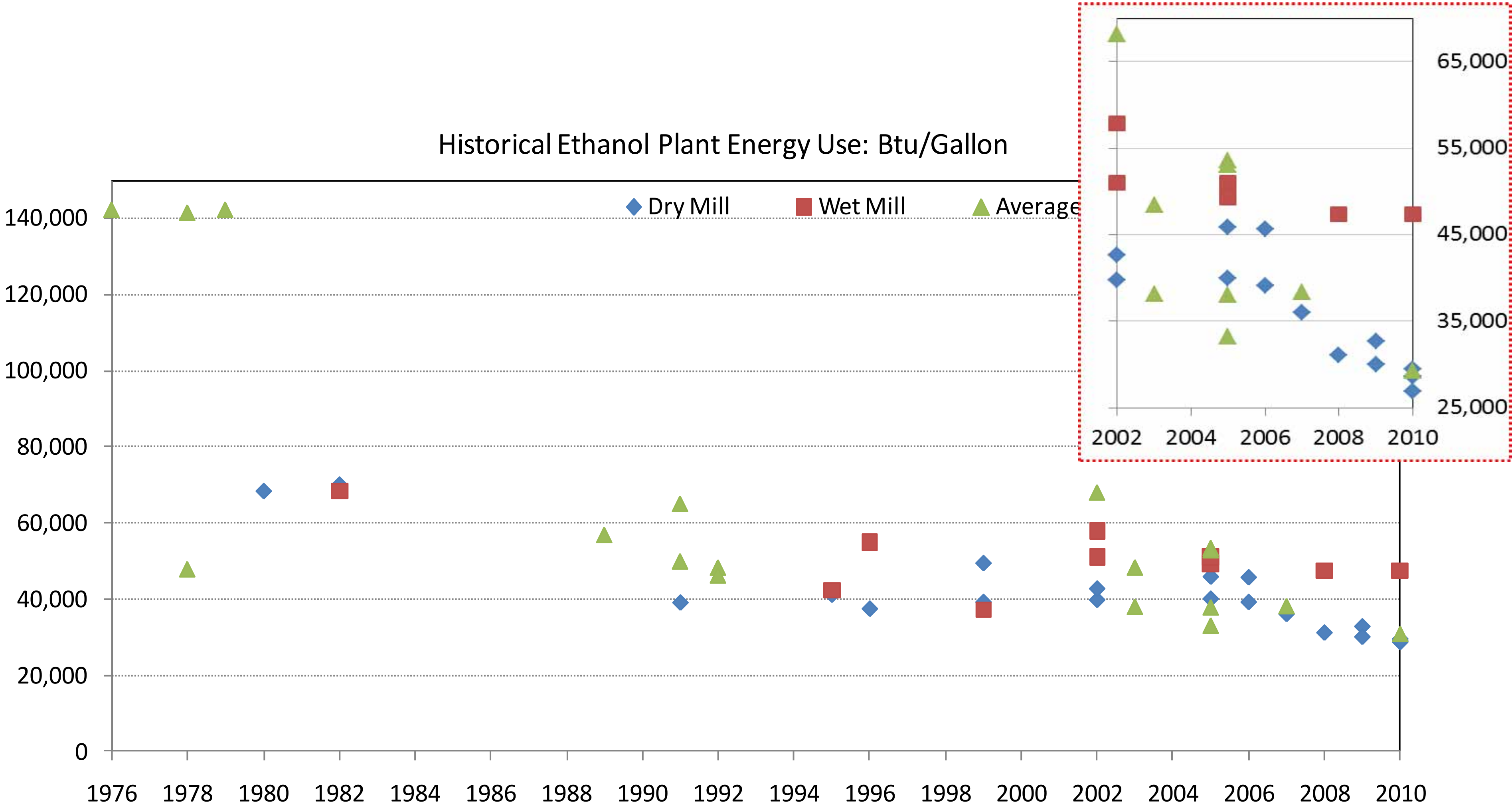
Life-Cycle Analysis System boundary: Dedicated Energy Crops to Cellulosic Ethanol



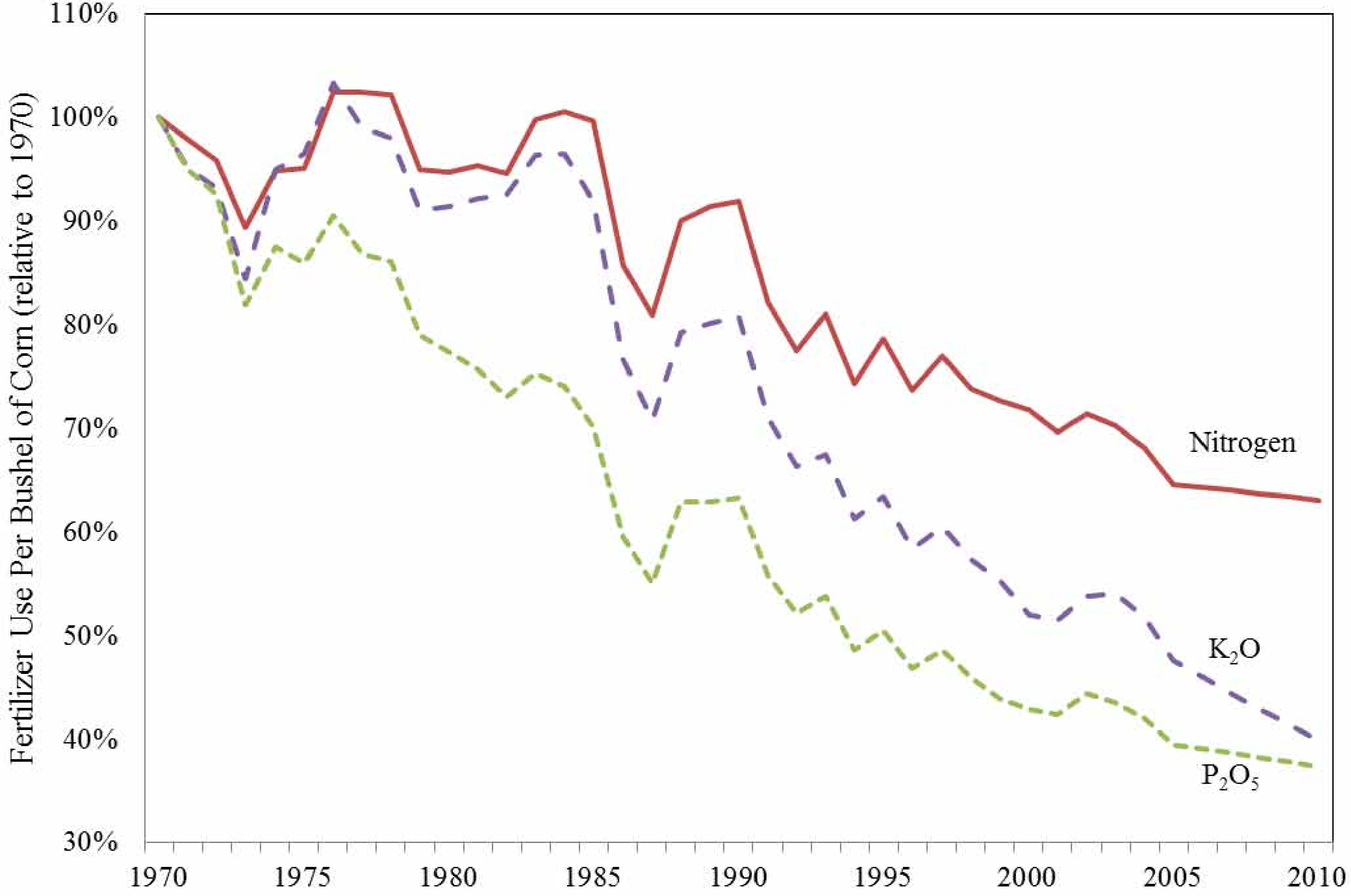
Key Issues Affecting Biofuel WTW Results

- Continued technology advancements
  - Agricultural farming: continued crop yield increase and resultant reduction of energy and chemical inputs per unit of yield
  - Energy use in ethanol plants: reduction in process fuel use and switch of process fuel types
- Methods of estimating emission credits of co-products of ethanol
- Direct and indirect land use changes and resulted GHG emissions
- Life-cycle analysis methodologies
  - Attributional LCA
  - Consequential LCA

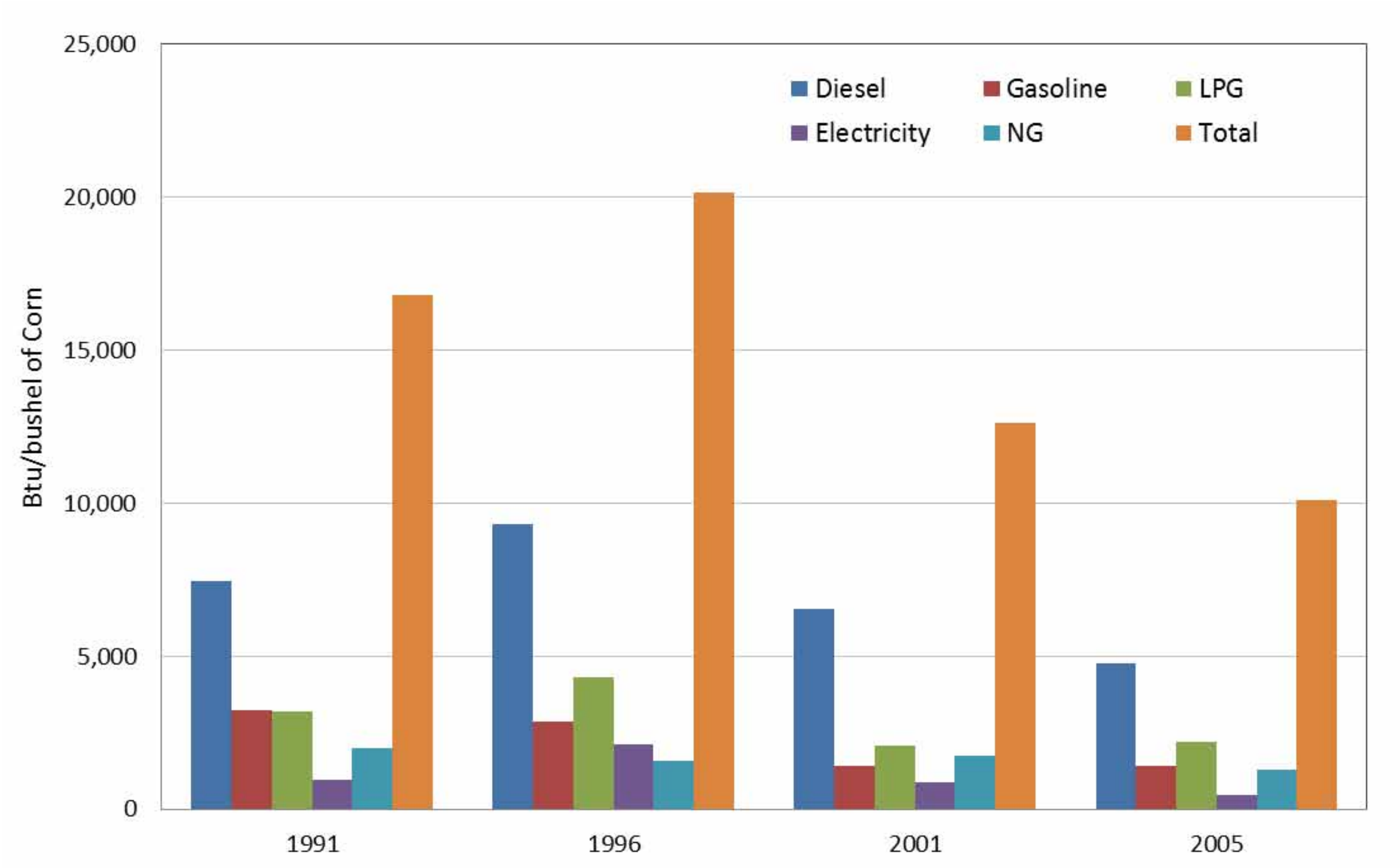
Trend of 35 Studies in the Past 35 Years: Energy Use in U.S. Corn Ethanol Plants Has Decreased Significantly



Fertilizer Use in U.S. Corn Farming Has Reduced Significantly in the Past 40 Years



Energy Use for Corn Farming Has Been Reduced



The unusual high farming energy use in 1996 may be caused by the wet weather in that year in the Midwest.

Intensity of Fertilizer Use in U.S. Corn Farming and Energy Use and GHG Emissions of Fertilizer Production and Use

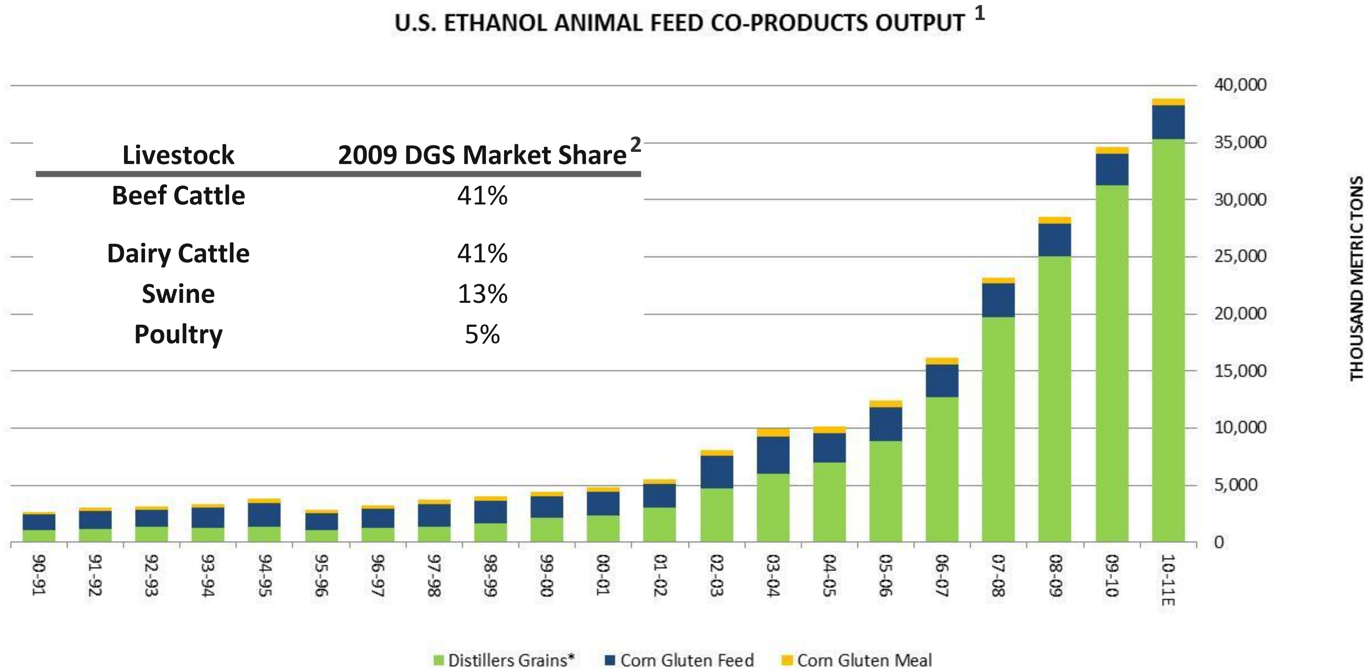
	Nitrogen	Phosphate	Potash	Lime
Fertilizer Use Intensity: lb of nutrient per bushel of corn	0.96	0.34	0.40	2.44
Energy Use for Fertilizer Production: Btu/lb of nutrient	20,741	5,939	3,719	3,398
GHG Emissions of Fertilizer Production: g CO_{2e}/lb of nutrient	1,359	460	302	274
GHG Emissions from Fertilizer in Field: g CO_{2e}/lb of nutrient	2,965[a]	0	0	200[b]
Total GHG Emissions: g CO2e/lb of fertilizer	4,324	460	302	474
Total GHG Emissions: g CO2e/bushel of corn	4,151	156	121	1,157

[a] This is CO_{2e} emissions of N_2O from nitrification and denitrification of nitrogen fertilizer in cornfields.
[b] This is CO_2 emissions of converting calcium carbonate (limestone) to calcium oxide (burnt lime) in cornfields.

Co-Product Methods: Benefits and Issues

- Displacement method
  - Data intensive: need detailed understanding of the displaced product sector
  - Dynamic results: fluctuate with economic and market modifications
- Allocation methods: based on mass, energy, or market revenue
  - Easy to use
  - Frequent updates not required for mature industry, e.g. petroleum refineries
  - Mass-based allocation: not applicable for certain cases
  - Energy-based allocation: less accurate with non-fuel co-products
  - Market revenue based allocation: subject to price variation
- Process energy use approach
  - Requires detailed engineering analysis
  - Must allocate upstream burdens based on mass, energy, or market revenue

Displacement Ratios between DGS and Conventional Animal Feeds



Livestock	2009 DGS Market Share [2]
Beef Cattle	41%
Dairy Cattle	41%
Swine	13%
Poultry	5%

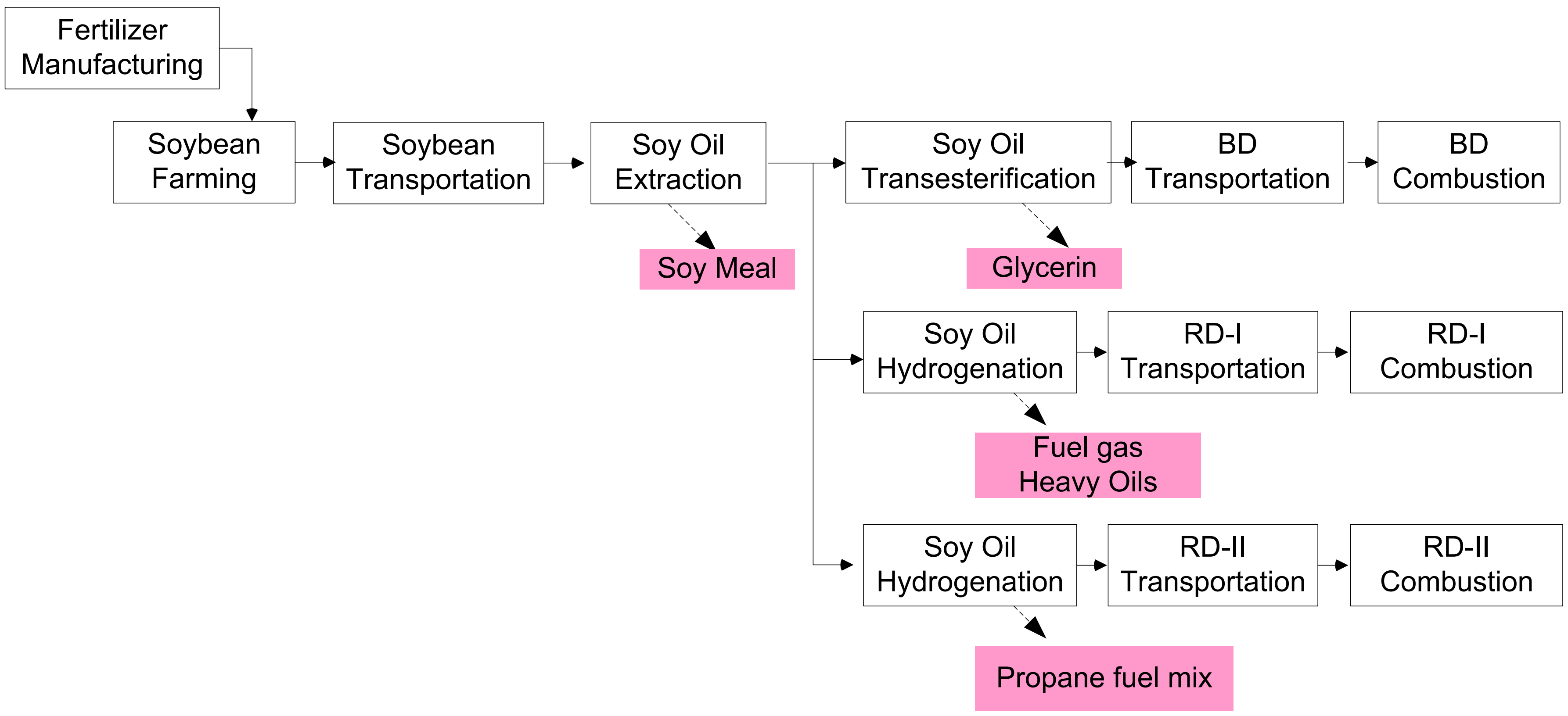
Displacement Ratio Between DGS and Conventional Feed (kg/kg of DGS) [2]
[Dry Matter Basis]

	Dry DGS			Wet DGS		
Livestock	Corn	Soybean Meal	Urea	Corn	Soybean Meal	Urea
Beef Cattle	1.203	0.000	0.068	1.276	0.000	0.037
Dairy Cattle	0.445	0.545	0.000	0.445	0.545	0.000
Swine	0.577	0.419	0.000			
Poultry	0.552	0.483	0.000			
Average	0.751	0.320	0.024			

Dry and Wet DGS Combined		
0.788	**0.304**	**0.022**

1. Renewable Fuels Association 2011
2. In Arora et al. 2010

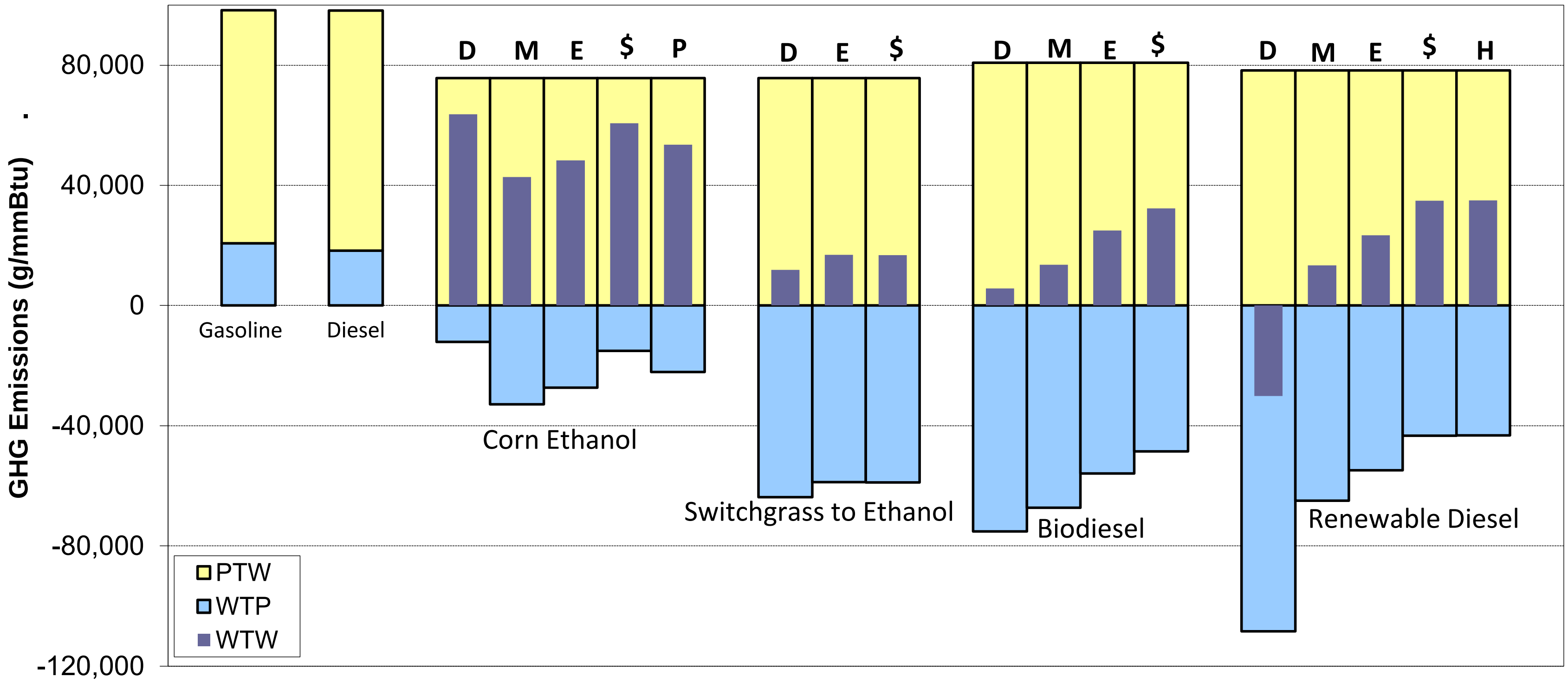
Significant Amount of Co-Products Is Produced with Soybean-Based Diesel Fuels



Share of co-products of the total outputs

	Mass	Energy	Market Price
Biodiesel	83%	68%	53%
Renewable Diesel I	88%	76%	61%
Renewable Diesel II	84%	67%	51%

Choice of Co-Product Methods Can Have Significant LCA Effects for Biofuels



D: Displacement
M: Mass based
E: Energy Based

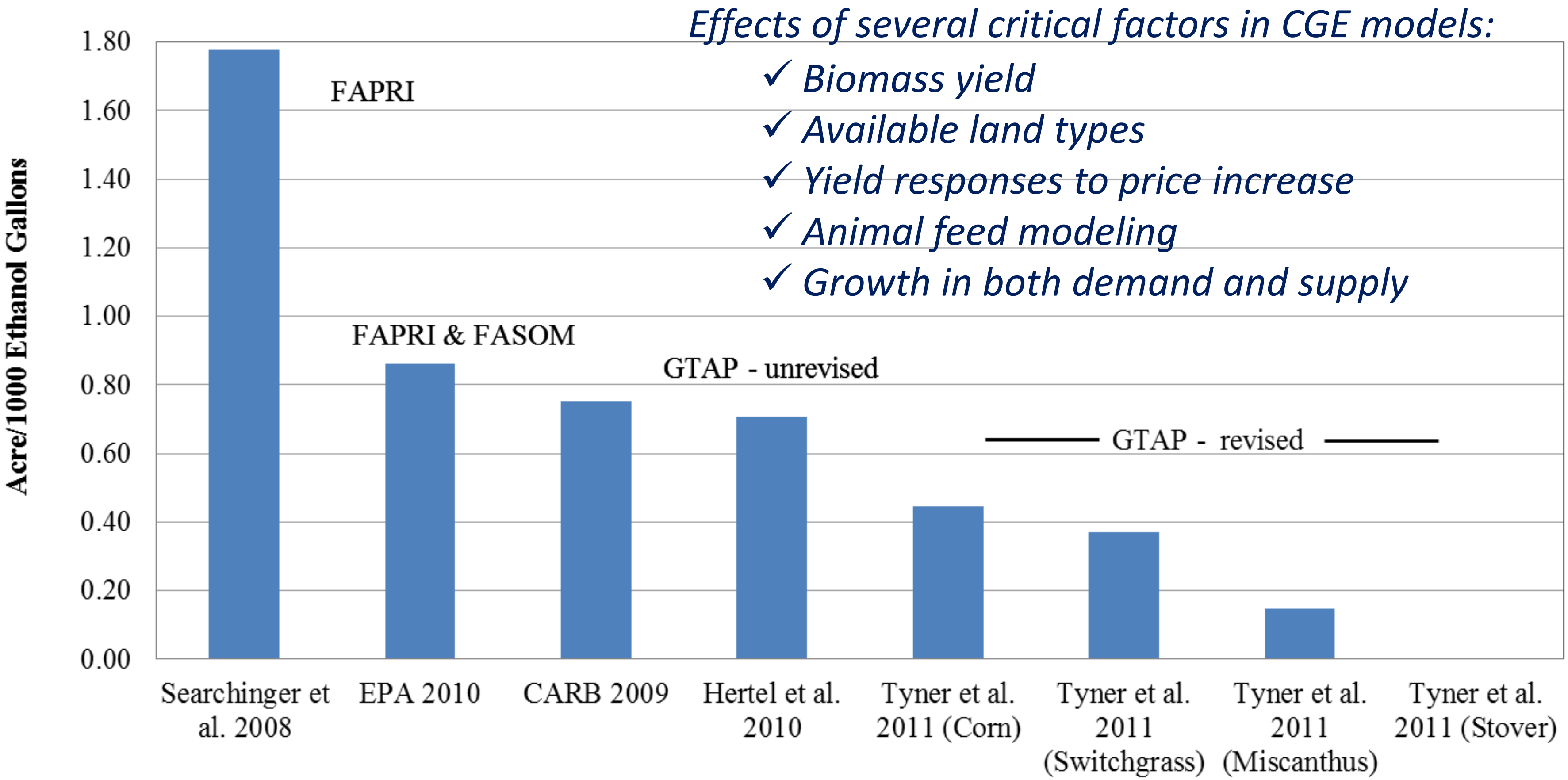
$: Market Value
P: Process Purpose
H: Hybrid Allocation

In Wang et al. (2010)

Key Steps to Address GHG Emissions of Potential Land Use Changes by Large-Scale Biofuel Production

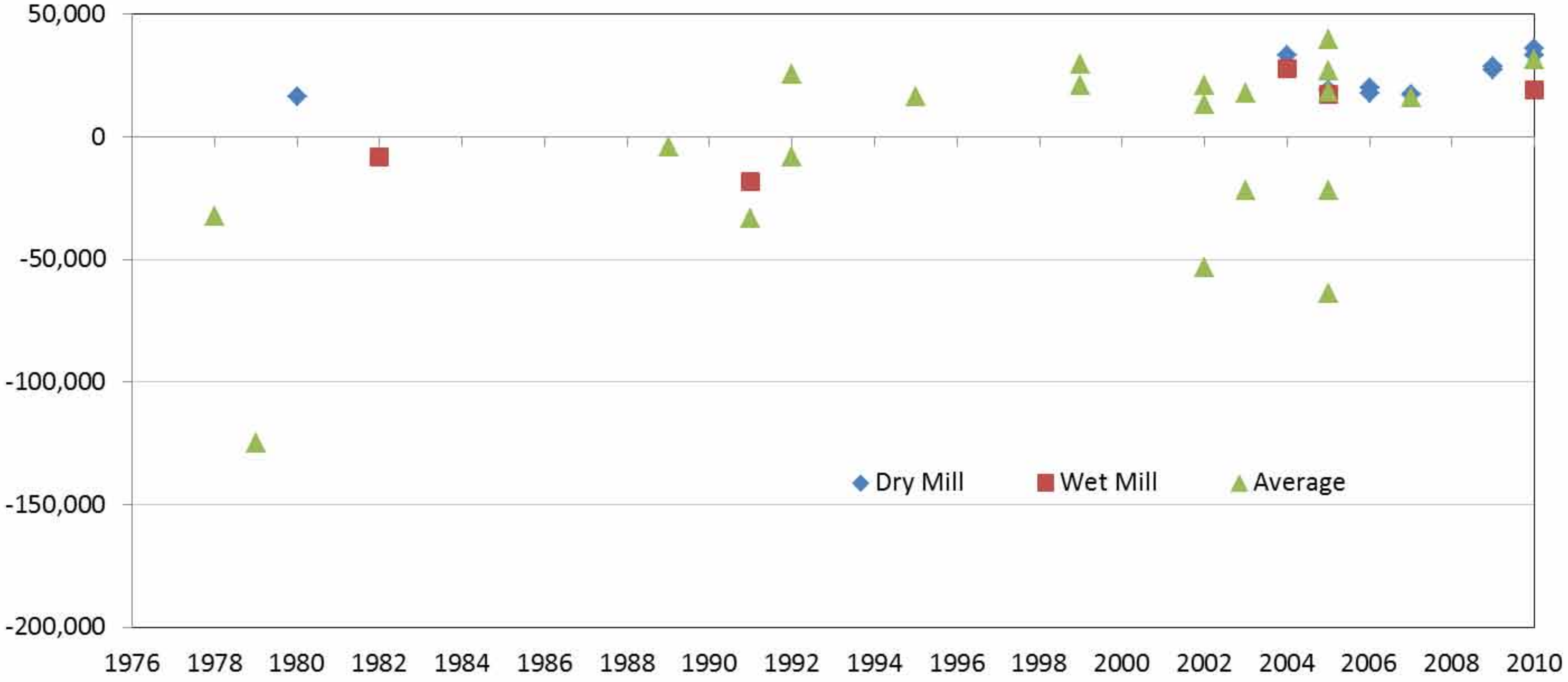
- Simulations of potential land use changes
  - Significant efforts have been made in the past three years to improve existing computational general equilibrium (CGE) models
  - More efforts are being made to address additional biomass feedstocks
- Carbon profiles of major land types
  - Both above-ground biomass and soil carbon are being considered
  - Of the available data sources, some are very detailed (e.g., the DAYCENT model) but others are very coarse (e.g., the IPCC data)
  - There are mismatches between CGE simulated land types and land types in available carbon databases
  - Soil depth for soil carbon could be a major issues when energy crops are to be simulated

Land Use Change Simulated for US Biofuel Production from Some Completed Studies



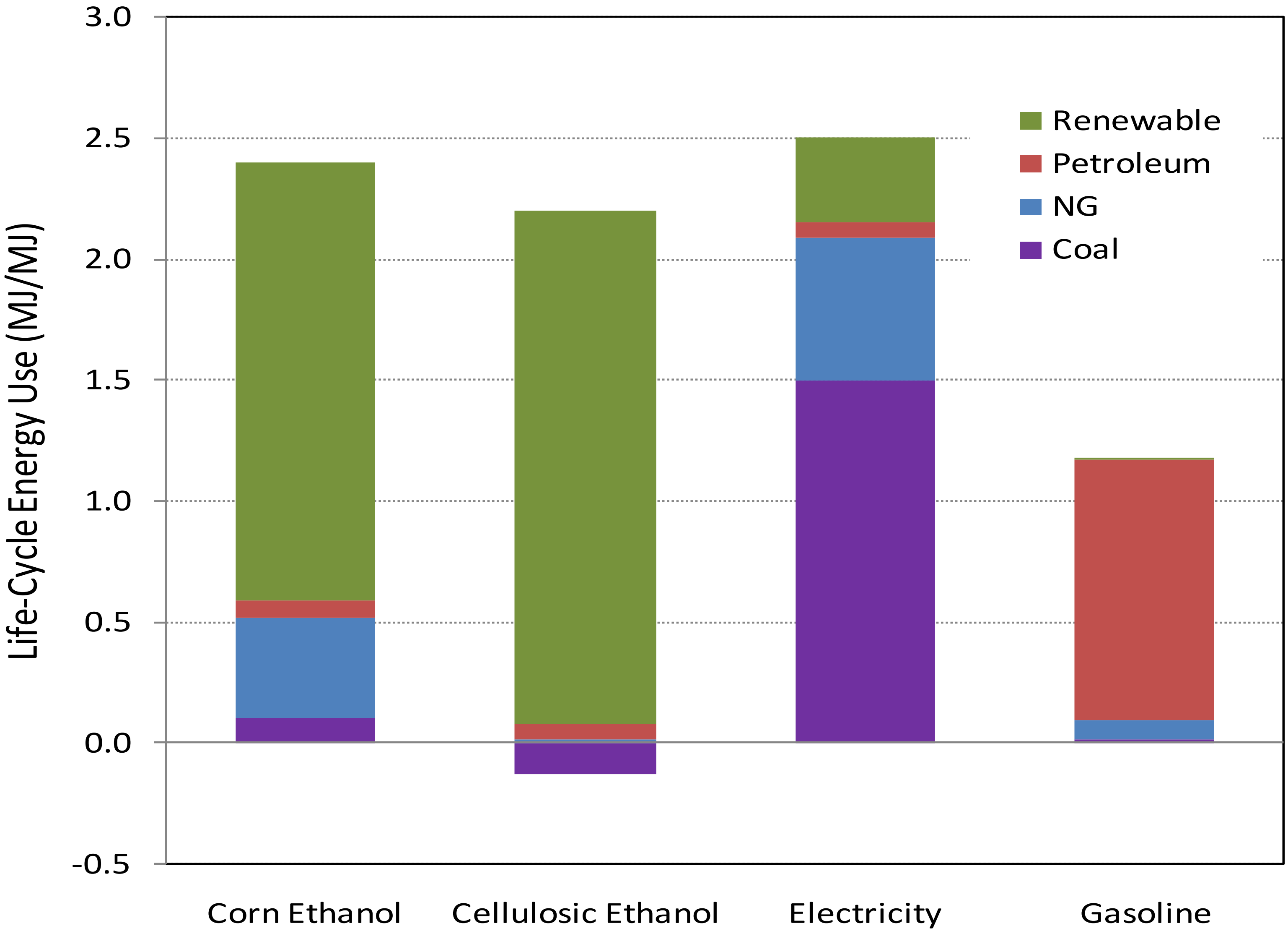
CGE – Computable General Equilibrium
GTAP – Global Trade Analysis Project (Purdue University)
FAPRI – Food and Agricultural Policy Research Institute (Iowa State)
FASOM – Forest and Agricultural Sector Optimization Model (Texas A&M)

Most Recent Studies Show Positive Net Energy Balance for Corn Ethanol

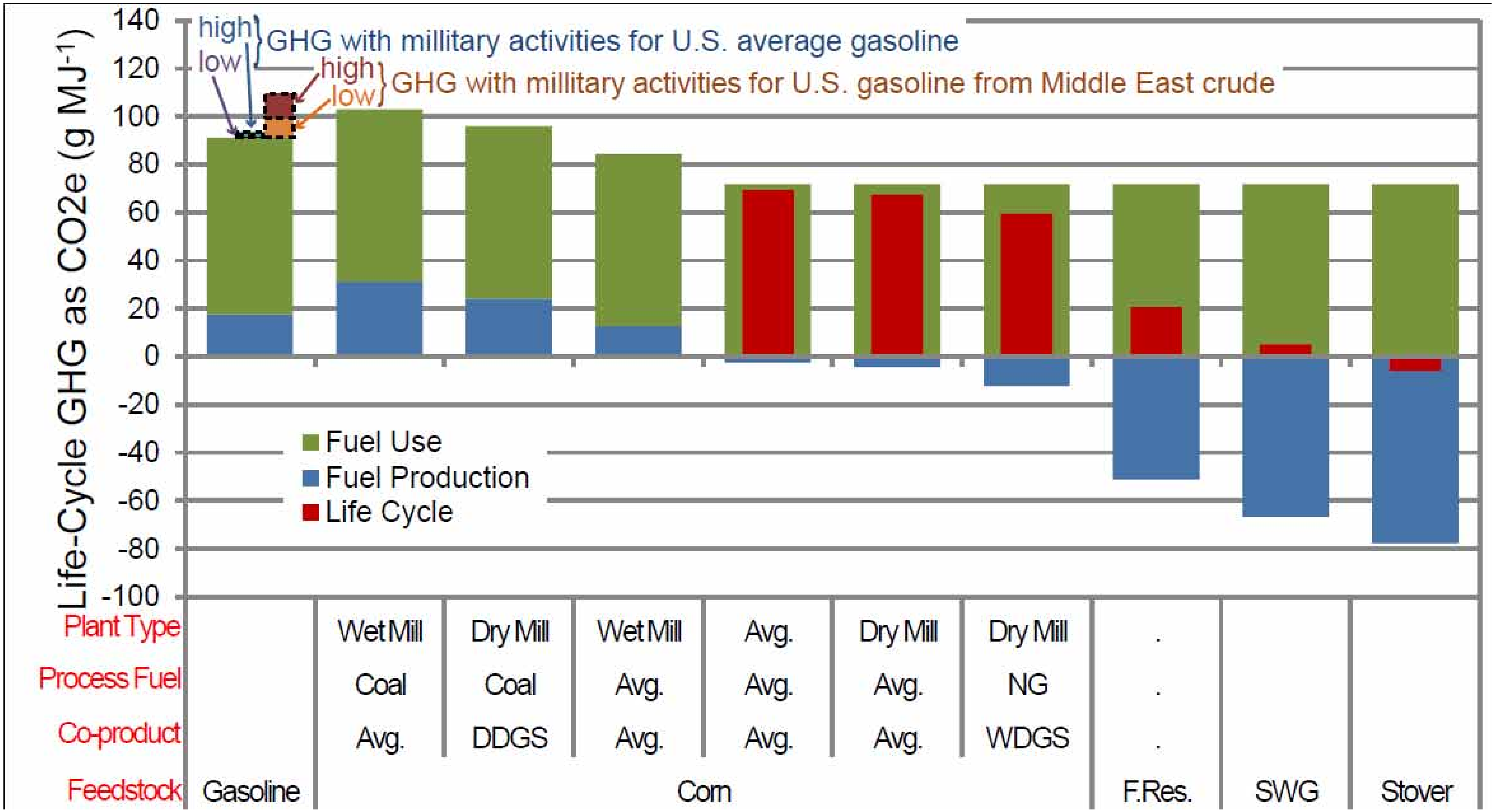


Energy balance here is defined as Btu content a gallon of ethanol minus fossil energy used to produce a gallon of ethanol

Energy Use by Type Varies Considerably Among Energy Products

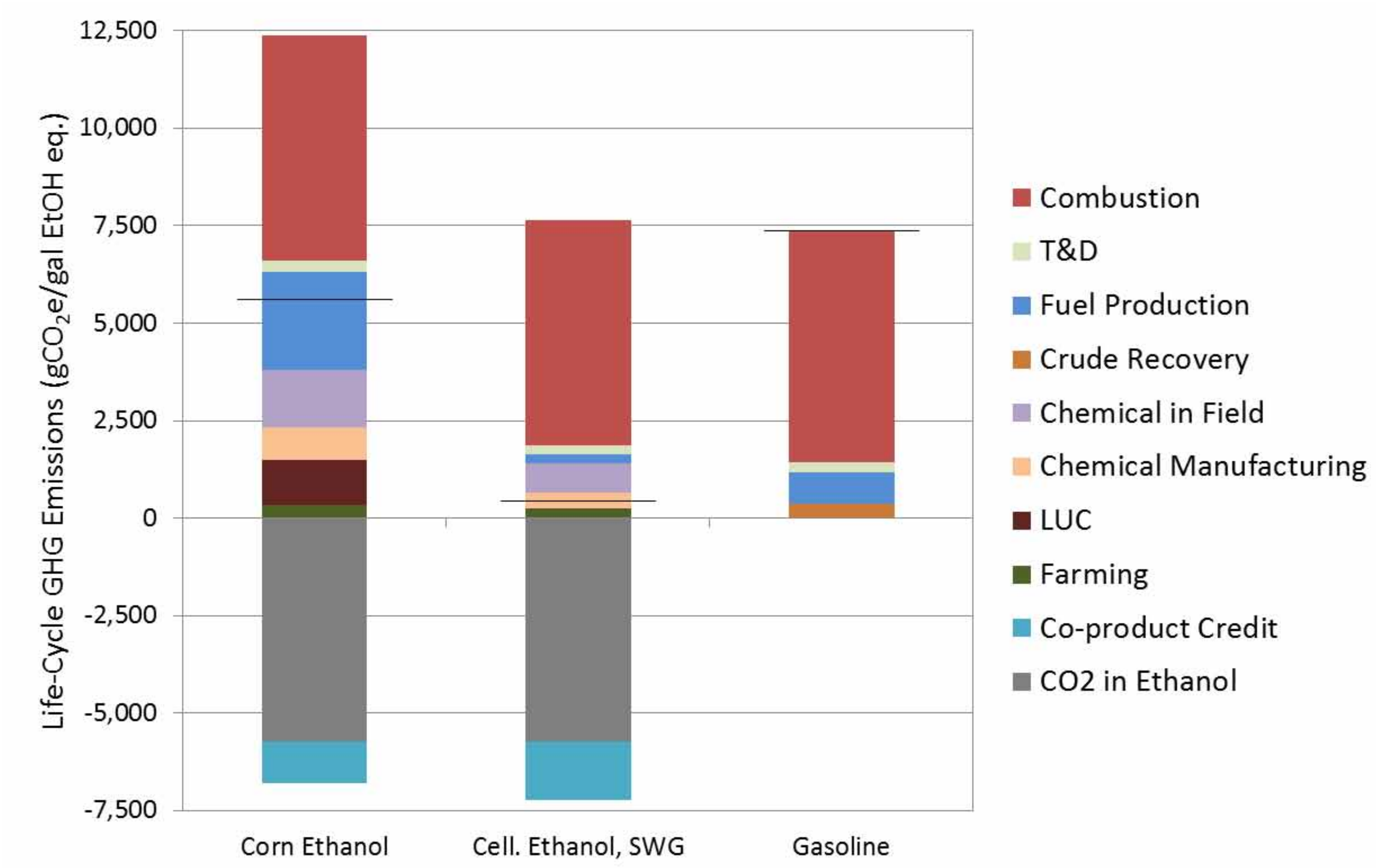


GHG Emissions of Corn Ethanol Vary Considerably Among Process Fuels in Plants; Cellulosic Ethanol Consistently Achieves Large Reductions

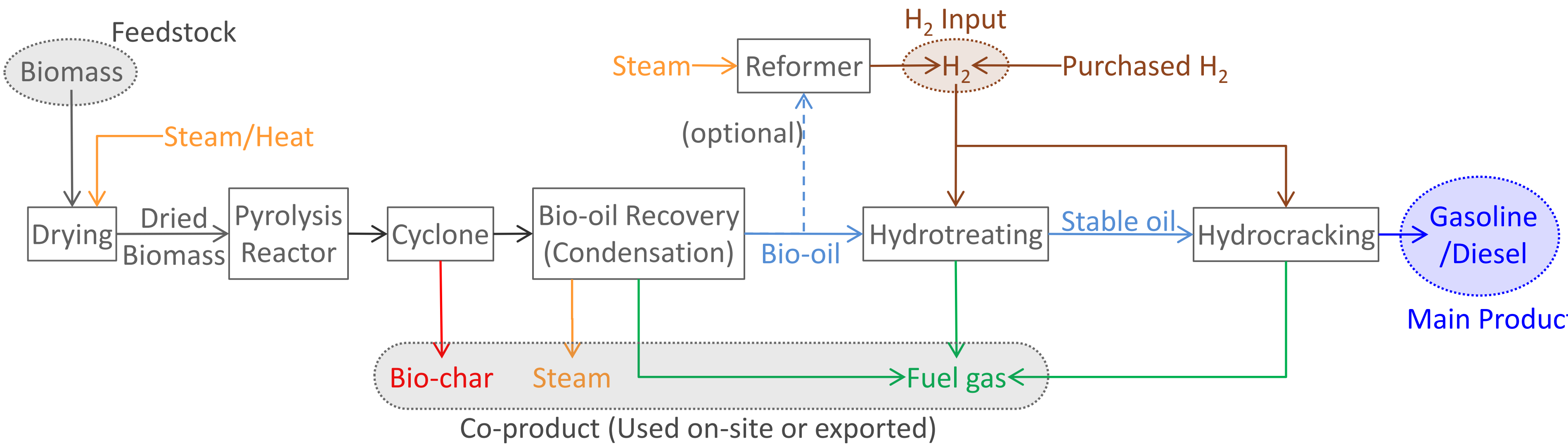


DDGS – dry DGS WDGS – wet DGS F.Res – forest residues SWG -- switchgrass

GHG Emission Sources of Ethanol and Gasoline



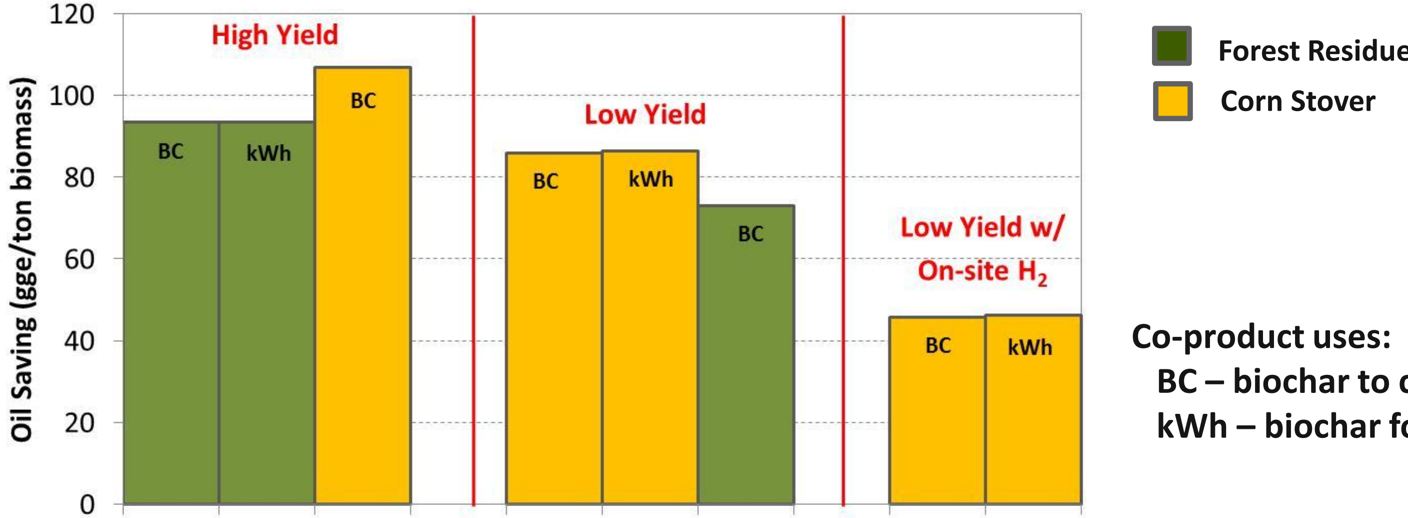
Key Issues in Pyrolysis Pathway LCA



- Liquid fuel yields
- Co-product bio-char yields and applications
  - Carbon sequestration in soil vs. as a fuel for electricity generation
- Amount and source of hydrogen for upgrading
  - Purchased hydrogen from NG SMR vs. internal hydrogen production
- Feedstocks, such as
  - Forest residue
  - Corn stover

Oil Savings and GHG Results of Pyrolysis Biofuels

Petroleum Savings Per Ton of Biomass Used (gasoline gallon equivalent)

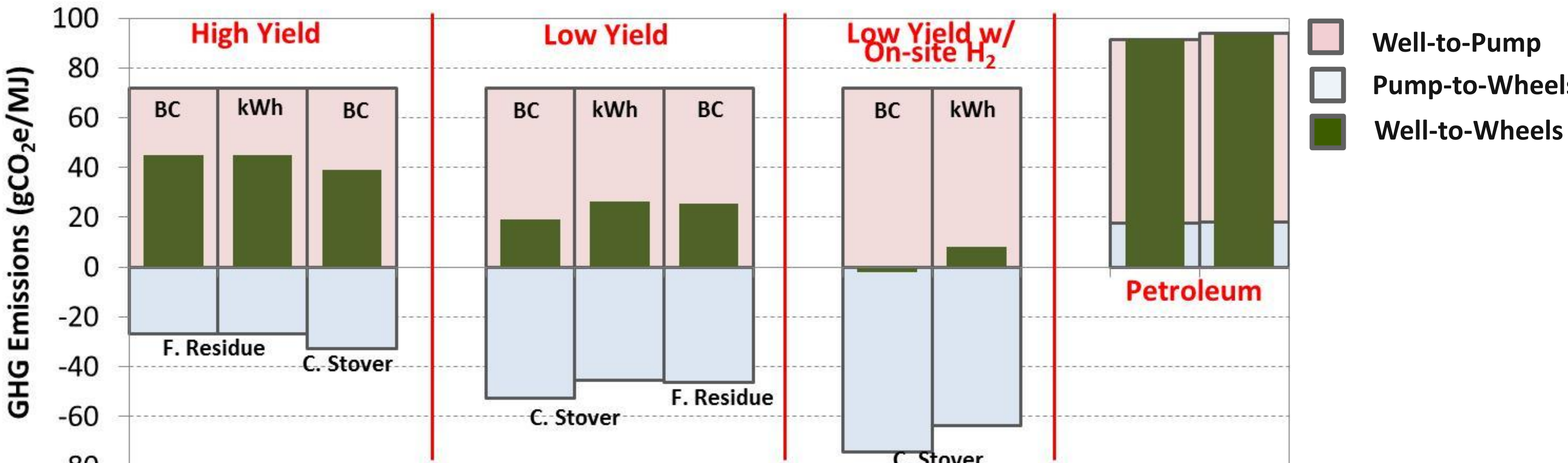


Co-product uses:

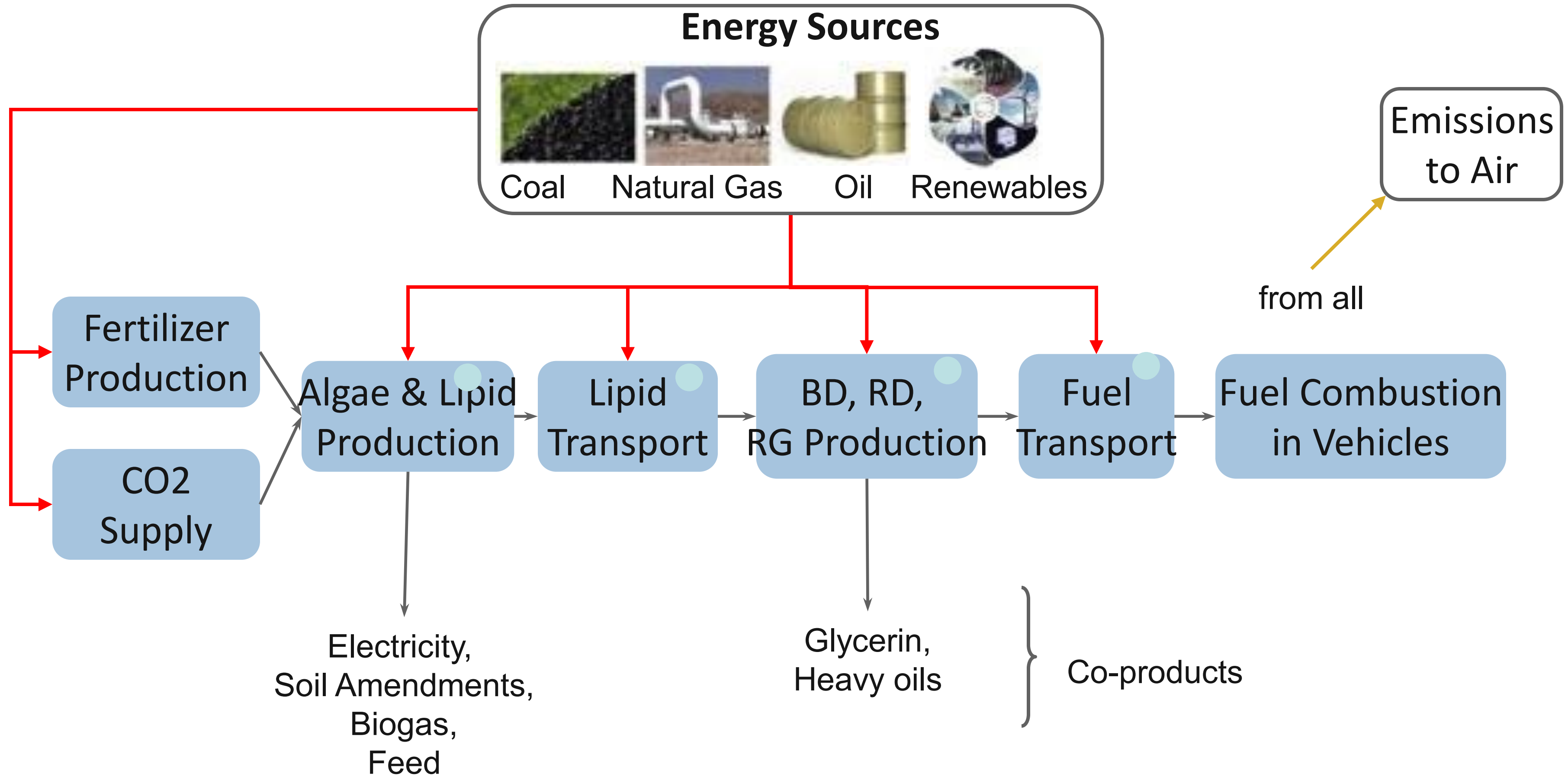
BC – biochar to carbon in soil

kWh – biochar for power generation

GHG Emissions per MJ of Fuel Produced and Used



Algae LCA System Boundary in GREET



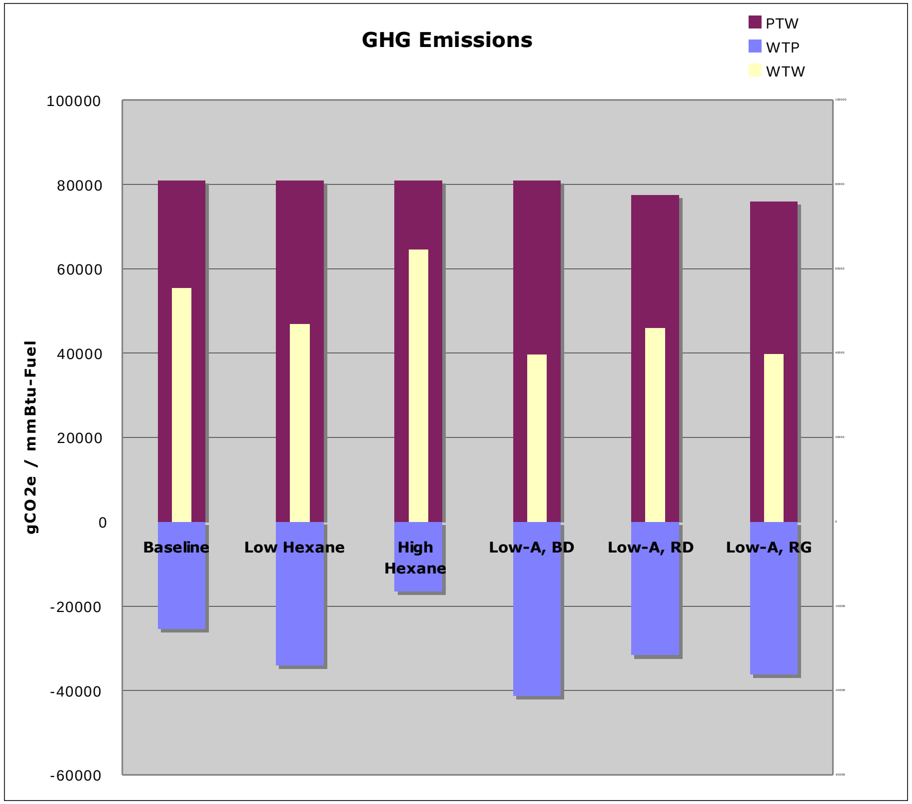
BD: biodiesel; RD: renewable diesel; RG: renewable gasoline
Currently excluded: infrastructure materials, land-use change

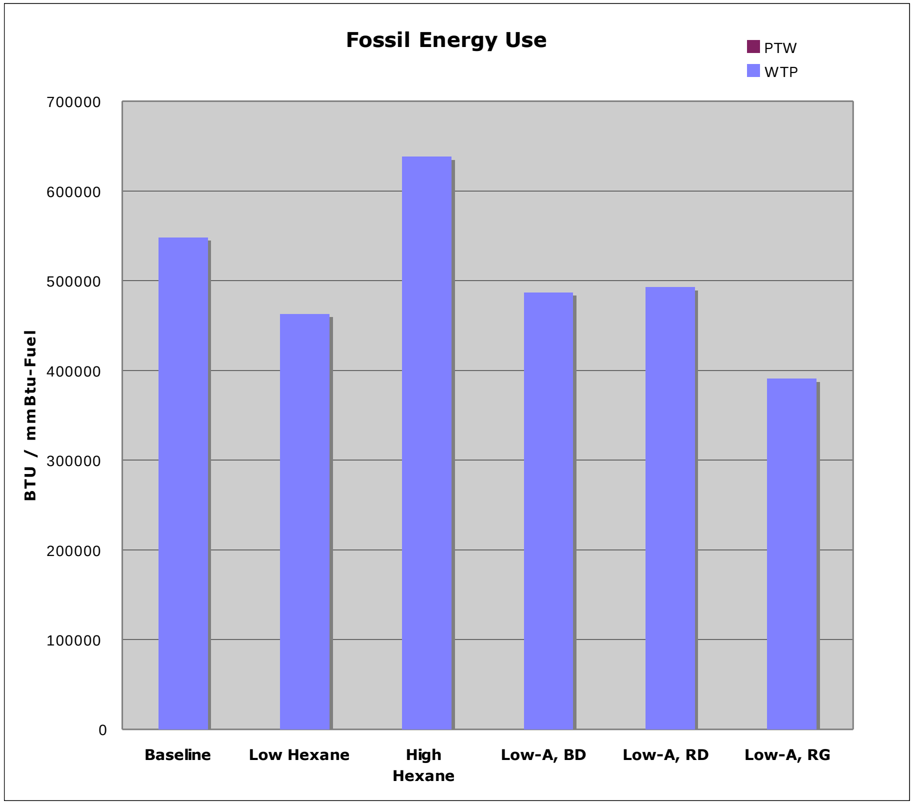
Algal Oil Extraction – Wet Hexane Extraction

- ❑ Theoretical process
- ❑ On-site, not regional, since wet (feasible scale?)
- ❑ Energy consumption via previous modeling studies:
  - ➢ Heat is obtained from the CHP system

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

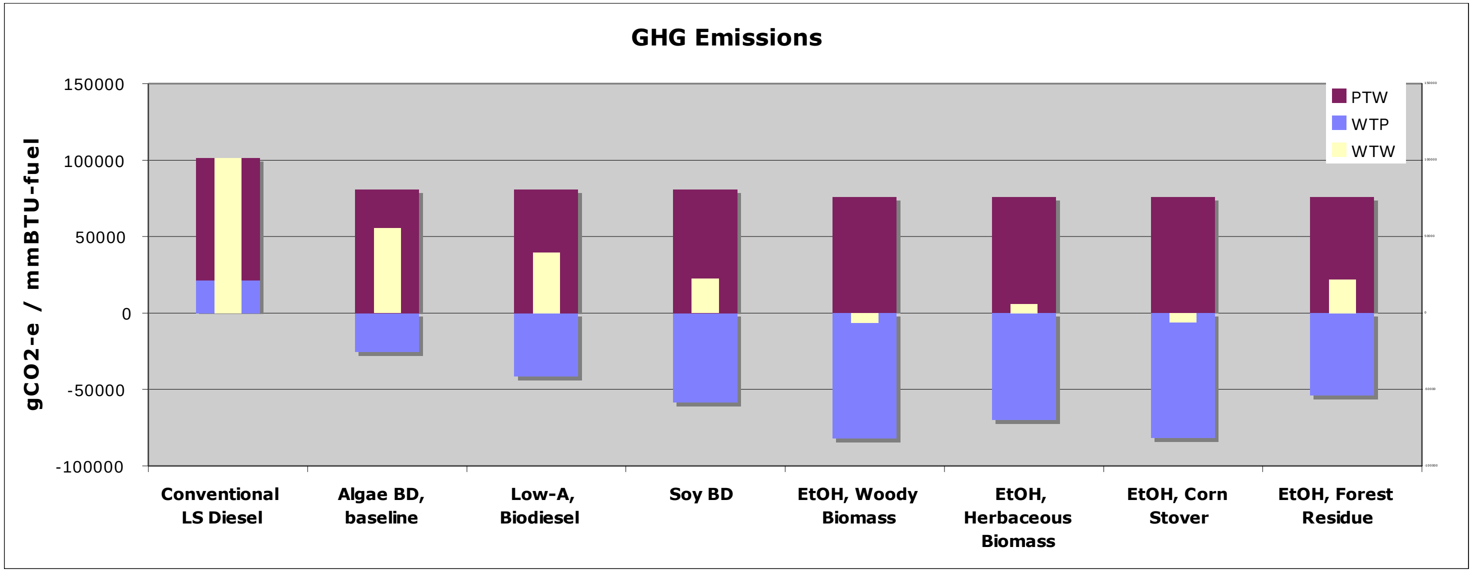
Energy and GHG Results: Alternative Oil Extraction Cases, RD and RG

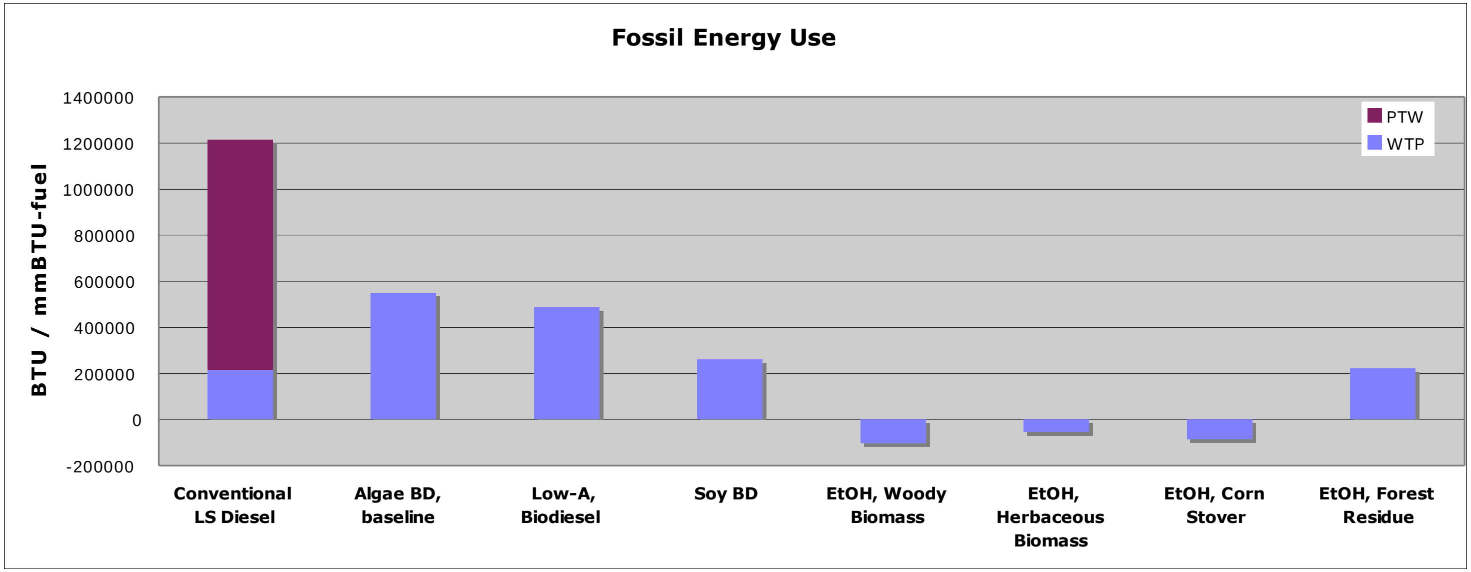




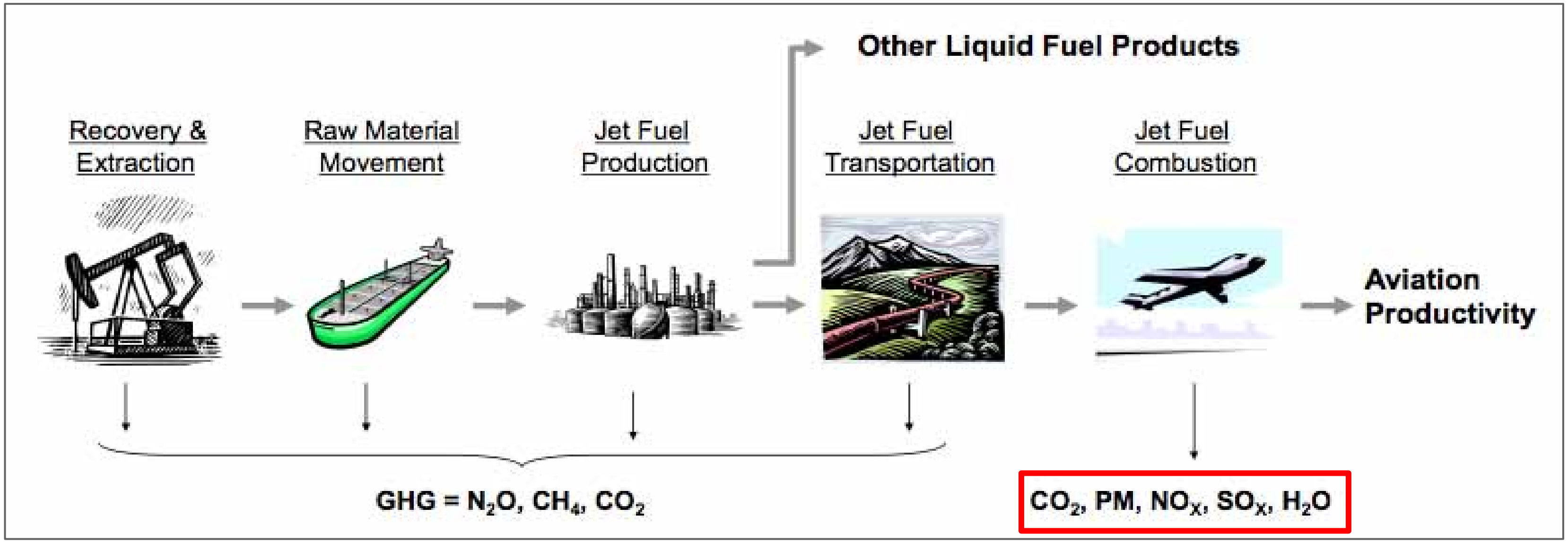
Low & High Hexane	Low and high energy consumption values (previous slide) during hexane-extraction of lipids.
Low-A	Decrease CHP electric efficiency from 33% to 29%; replace AD with catalytic hydrothermal gasification; increase lipid fraction in the algae to 30%
RD, RG	Renewable diesel, renewable gasoline from Low-A scenario.

Energy and GHG Results: Algae vs. Other Fuels

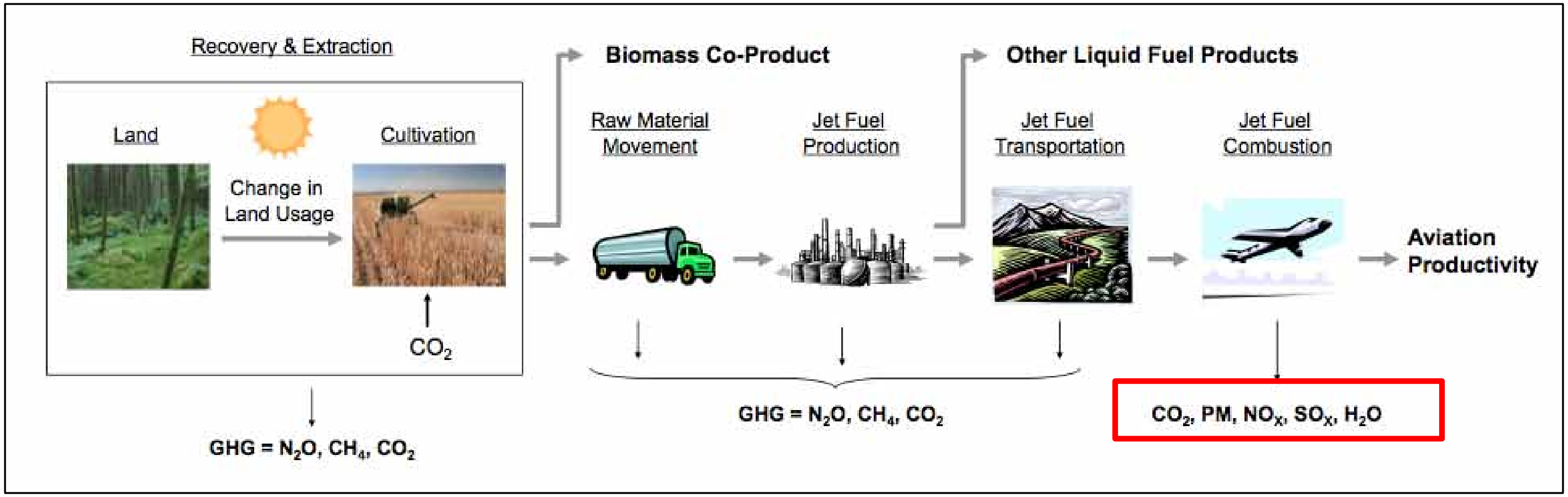




Jet Fuel LCA in GREET



Conventional Jet Fuel



From Nick Carter and James Hileman of MIT.

Aviation Fuel Options in the New GREET Version

Fuels and Feedstocks

- Petroleum Jet Fuel
  - Conventional Crude
  - Oil Sand
- Pyrolysis Oil Jet Fuel
  - Crop Residues
  - Forest Residues
  - Dedicated Energy Crops
- Hydrotreated Renewable Jet Fuel
  - Soybeans
  - Palm Oil
  - Rapeseeds
  - Jatropha
  - Camelina
  - Algae
- Fischer-Tropsch Jet Fuel
  - North American Natural Gas
  - Non-North American Natural Gas
  - Renewable Natural Gas
  - Shale Gas
  - Biomass via Gasification
  - Coal via Gasification
  - Coal/Biomass via Gasification

Aircraft Types

- Passenger Aircraft
  - Single Aisle
  - Small Twin Aisle
  - Large Twin Aisle
  - Large Quad
  - Regional Jet
  - Business Jet
- Freight Aircraft
  - Single Aisle
  - Small Twin Aisle
  - Large Twin Aisle
  - Large Quad
- LCA Functional Units
  - Per MJ of fuel
  - Per kg-km
  - Per passenger-km

Summary

- A New GREET version (GREET1.2011) will be released in Sept. 2011
- For biofuels, the new version will have
  - Land use change GHG emissions for corn stover, switchgrass, and miscanthus (besides corn)
  - Pyrolysis-based diesel and gasoline production from corn stover and forest residues
  - Algae-based biodiesel, renewable diesel, and renewable gasoline
  - Renewable aviation fuels from oilseeds and cellulosic biomass
- Gaseous fuels
  - Shale gas
  - Renewable natural gas from landfill gas and anaerobic digestion of animal waste