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Life-Cycle Analysis of Biofuels With The GREET Model

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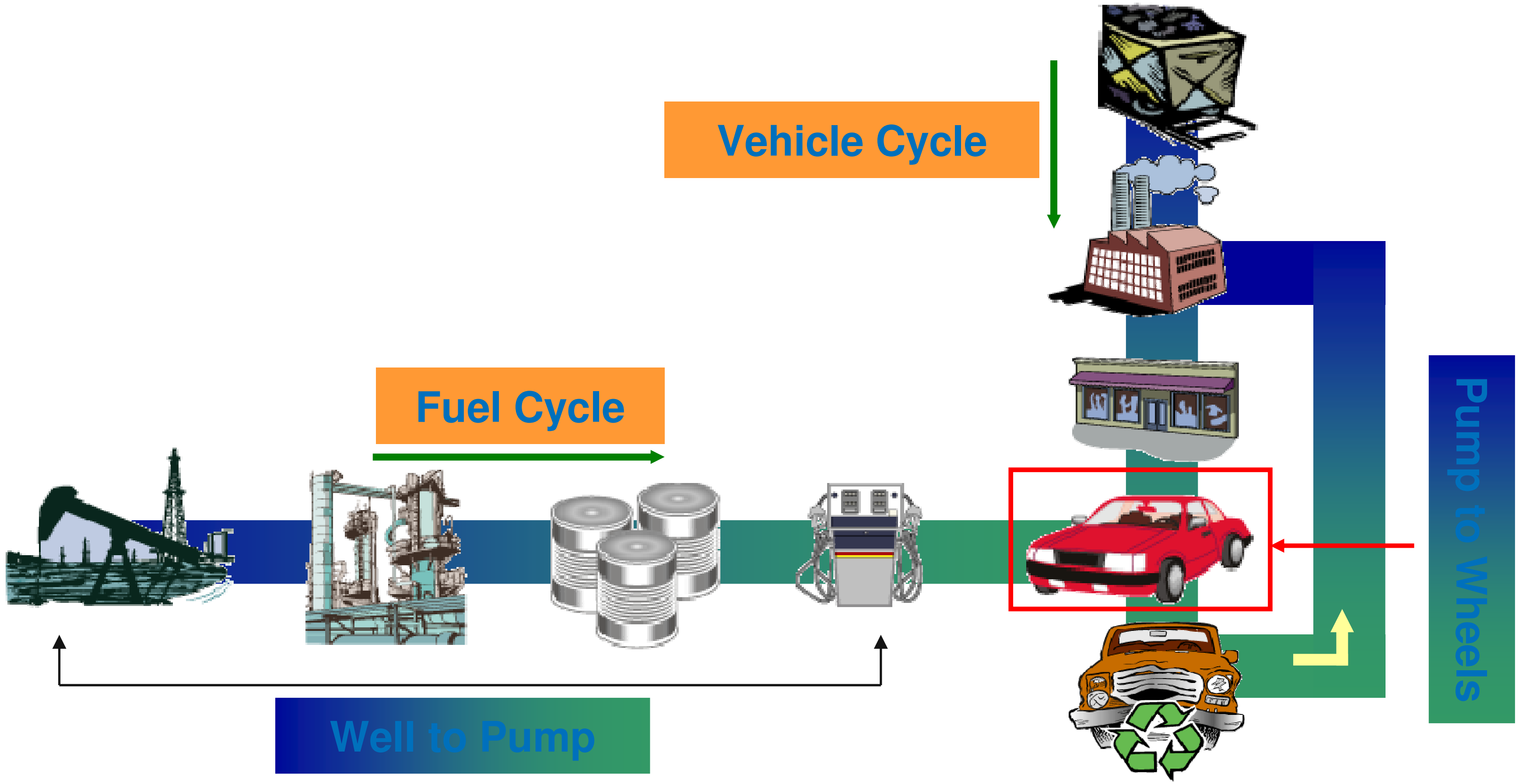
Well-to-Wheels Analysis of Vehicle/Fuel Systems Covers Activities for Fuel Production and Vehicle Use



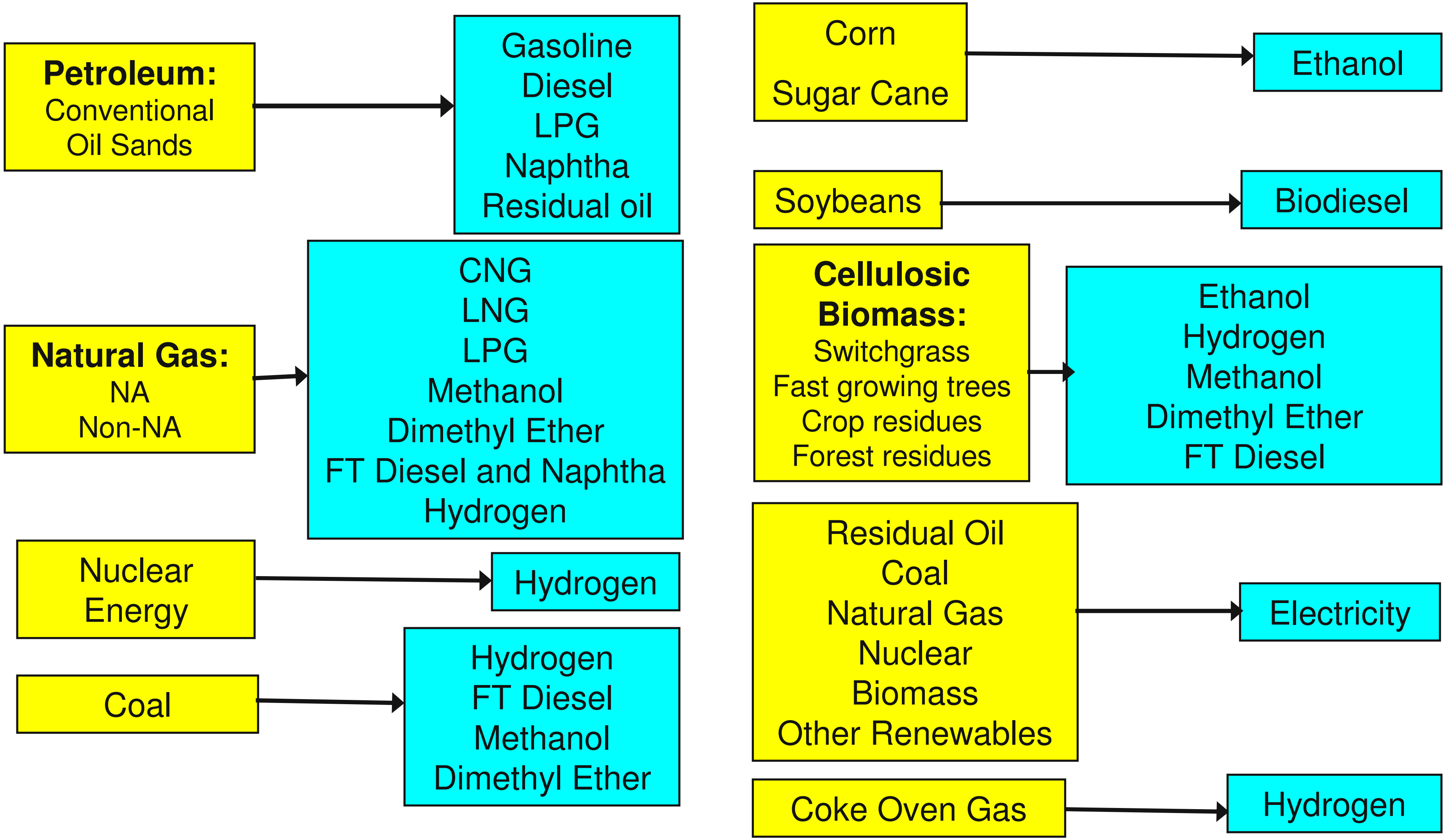
LCA Models have Been Developed to Examine Transportation Fuels and Vehicle Technologies

- The lifecycle emission model (LEM) at University of California at Davis
- The GREET model at Argonne National Laboratory
- Canadian GHGenius model (developed from an early LEM version)
- LBST's E3 database in Europe
- The Ecobalance model by PriceWaterhouseCooper in Europe
- Other generic LCA models that can be applied to examine transportation fuels and vehicle technologies

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

- **Argonne began GREET development in 1995 with DOE support**
- **Includes emissions of greenhouse gases**
  - CO_2, CH_4, and N_2O (and optional GHGs such as VOC, CO, and NO_x)
- **Estimates emissions of six criteria pollutants**
  - VOC, CO, NO_x, SO_x, PM_{10}, and $PM_{2.5}$
  - Total and urban separately
- **Separates energy use into**
  - All energy sources (fossil and non-fossil)
  - Fossil fuels (petroleum, natural gas, and coal combined)
  - Petroleum
  - Coal
  - Natural gas
- **GREET is in public domain**
  - Available at *http://www.transportation.anl.gov/software/GREET/ (or simply Google GREET on the Web)*
  - At present, there are more than 3,500 registered GREET users worldwide
  - The most recent GREET version was released in August 2007

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



GREET Includes More Than 75 Vehicle/Fuel Systems

Conventional Spark-Ignition Vehicles

- Conventional gasoline, federal reformulated gasoline, California reformulated gasoline
- Compressed natural gas, liquefied natural gas, and liquefied petroleum gas
- Gaseous and liquid hydrogen
- Methanol and ethanol

Spark-Ignition Hybrid Electric Vehicles: Grid-Independent and Connected

- Conventional gasoline, federal reformulated gasoline, California reformulated gasoline
- Compressed natural gas, liquefied natural gas, and liquefied petroleum gas
- Gaseous and liquid hydrogen
- Methanol and ethanol

Compression-Ignition Direct-Injection Vehicles

- Conventional diesel, low sulfur diesel, dimethyl ether, Fischer-Tropsch diesel, E-diesel, and biodiesel

Compression-Ignition Direct-Injection Hybrid Electric Vehicles: Grid-Independent and Connected

- Conventional diesel, low sulfur diesel, dimethyl ether, Fischer-Tropsch diesel, E-diesel, and biodiesel

Battery-Powered Electric Vehicles

- U.S. generation mix
- California generation mix
- Northeast U.S. generation mix
- User-selected generation mix

Fuel Cell Vehicles

- Gaseous hydrogen, liquid hydrogen, methanol, federal reformulated gasoline, California reformulated gasoline, low sulfur diesel, ethanol, compressed natural gas, liquefied natural gas, liquefied petroleum gas, and naphtha

Spark-Ignition Direct-Injection Vehicles

- Conventional gasoline, federal reformulated gasoline, and California reformulated gasoline
- Methanol and ethanol

Among Various Biofuel Production Pathways, GREET Includes Only Some

- Sugar Crops for EtOH
  - **<u>Sugar cane</u>**
  - Sugar beet
  - Sweet sorghum

- Starch Crops for EtOH
  - **<u>Corn</u>**
  - Wheat
  - Cassava
  - Sweet potato

- Butanol Production
  - **<u>Corn</u>**
  - Sugar beet

- Cellulosic Biomass via Gasification
  - **<u>Fitscher-Tropsch diesel</u>**
  - **<u>Hydrogen</u>**
  - Methanol

- Oils for <u>Biodiesel/Renewable Diesel</u>
  - **<u>Soybeans</u>**
  - Rapeseed
  - Palm oil
  - Jatropha
  - Waste cooking oil
  - Animal fat

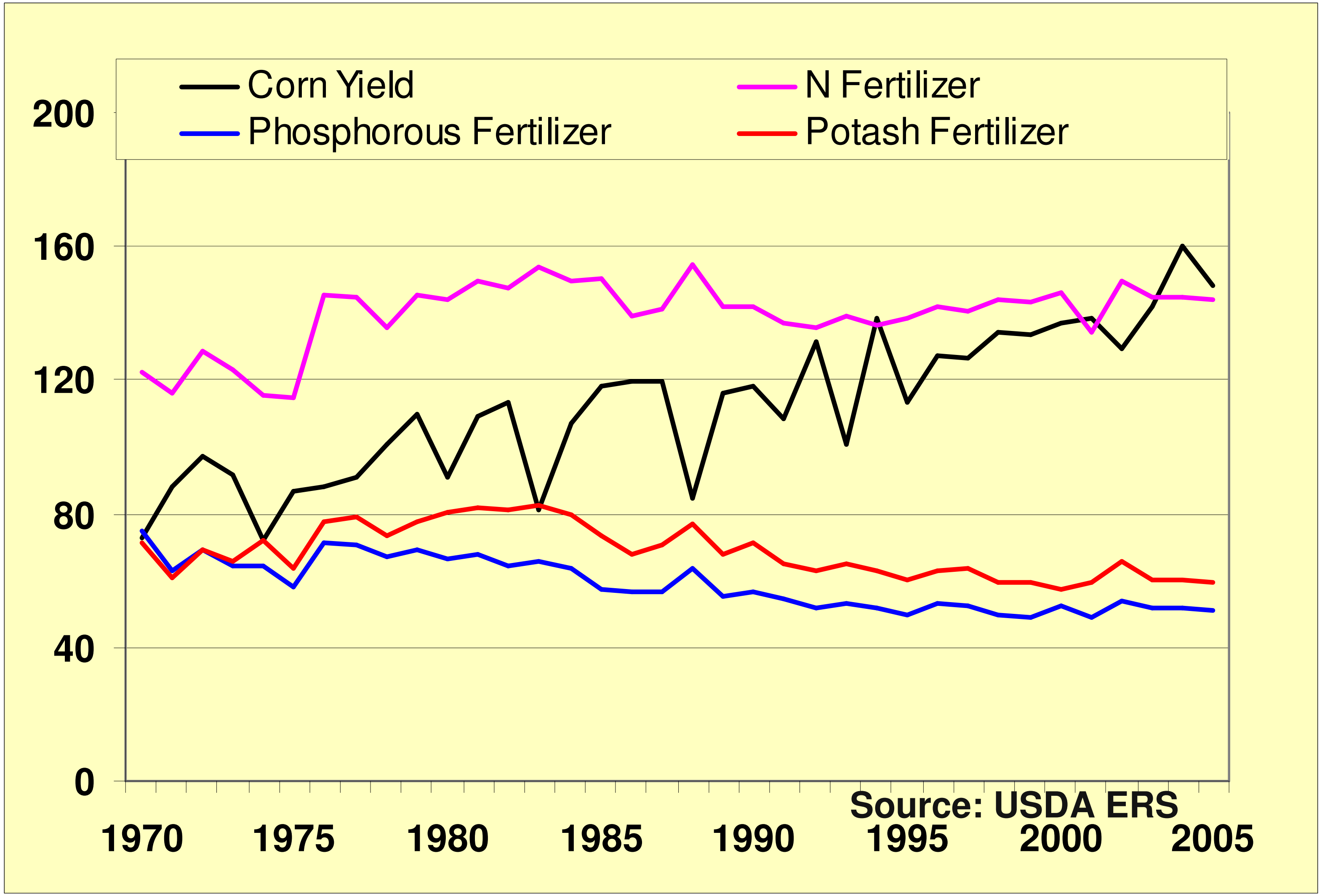
- Cellulosic Biomass for EtOH
  - **<u>Corn stover</u>**, rice straw, wheat straw
  - **<u>Forest wood residue</u>**
  - Municipal solid waste
  - **<u>Energy crops</u>**
  - Black liquor

The feedstocks that are underlined are already included in the GREET model.

Key Issues for Biofuel Life-Cycle Analysis

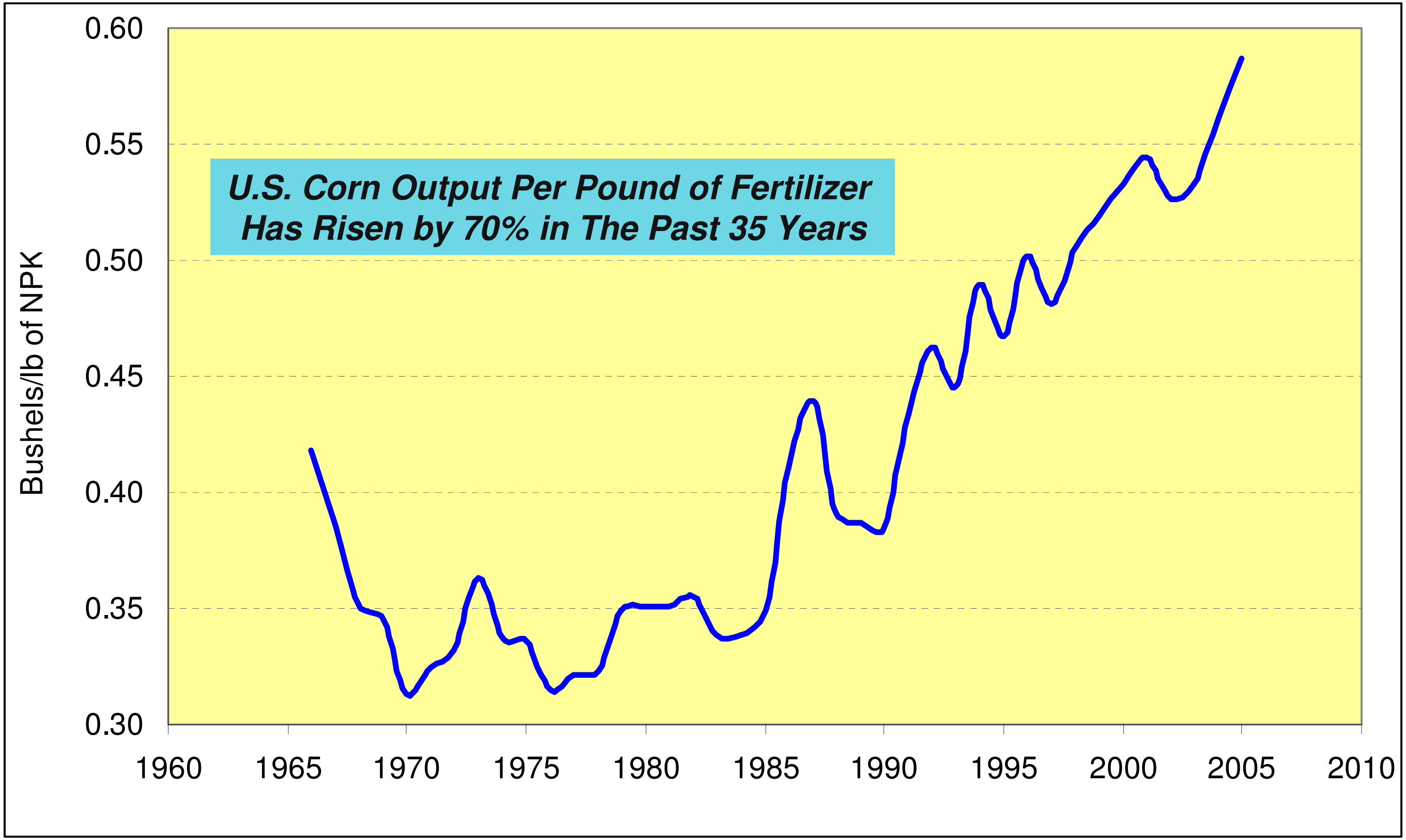
- Nitrogen fertilizer production: primarily from natural gas and a small amount from coal
- Use of fertilizer in farms
  - Nitrogen fertilizer: energy in fertilizer and N2O emissions from N nitrification and denitrification
  - Lime: CO2 emissions from lime stone (CaCO3) to lime (CaO) in fields for stabilizing soil acidity
- Energy use for farming
- Open field burning in sugarcane plantations
- Nitrogen cycle and resultant N2O emissions
- Energy use in biofuel plants
  - The amount of process fuels for steam production
  - The type of process fuels
- Co-products
- Land use change and resulted CO2 emissions

U.S. Fertilizer Use for Corn Farming Has Stabilized or Declined, While Corn Yield Continues to Increase



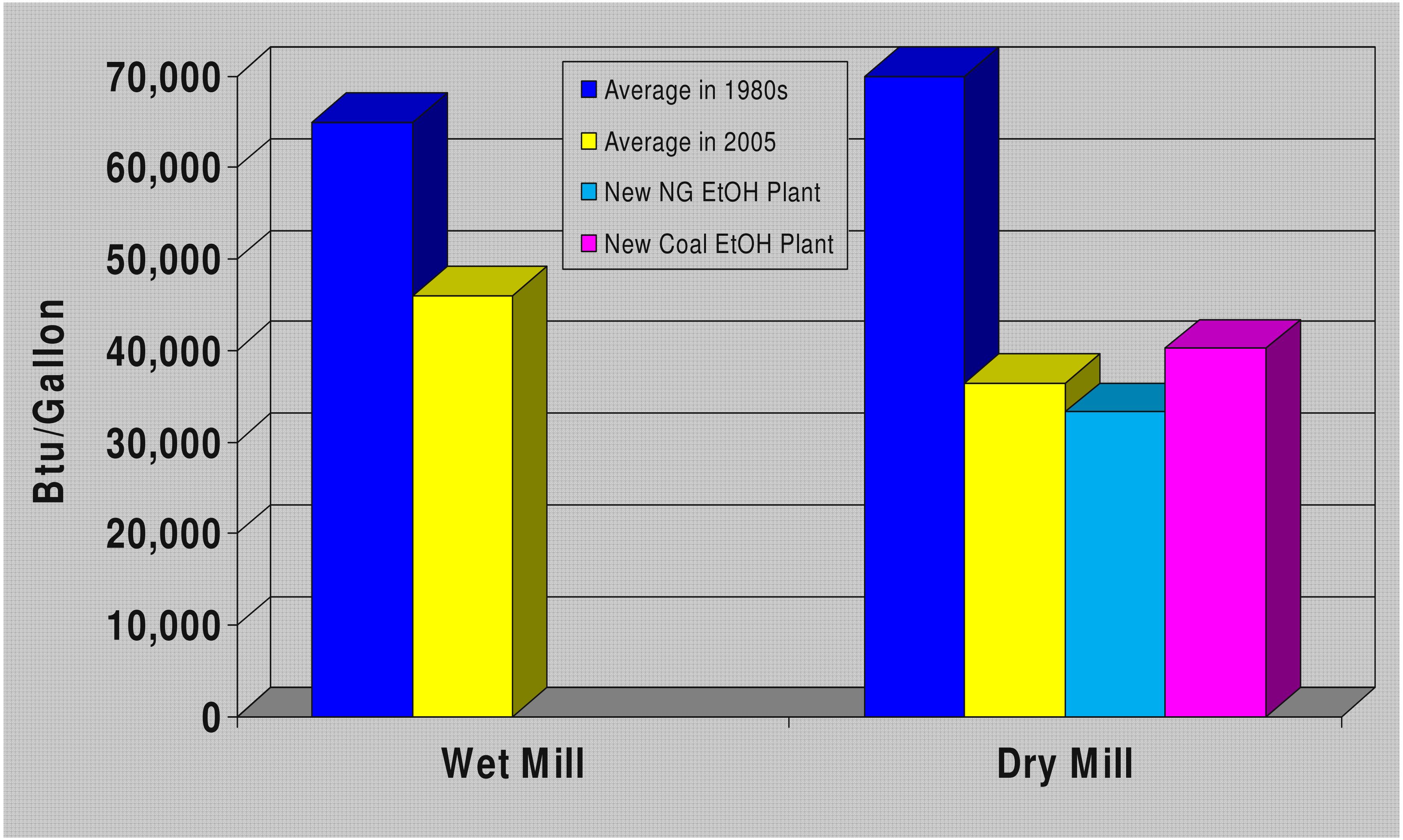
Corn yield is in bushels/acre; Fertilizer use is in lbs/acre.

Accurate LCA for Corn Ethanol Need to Account for Increased Productivity in Farming Over Time



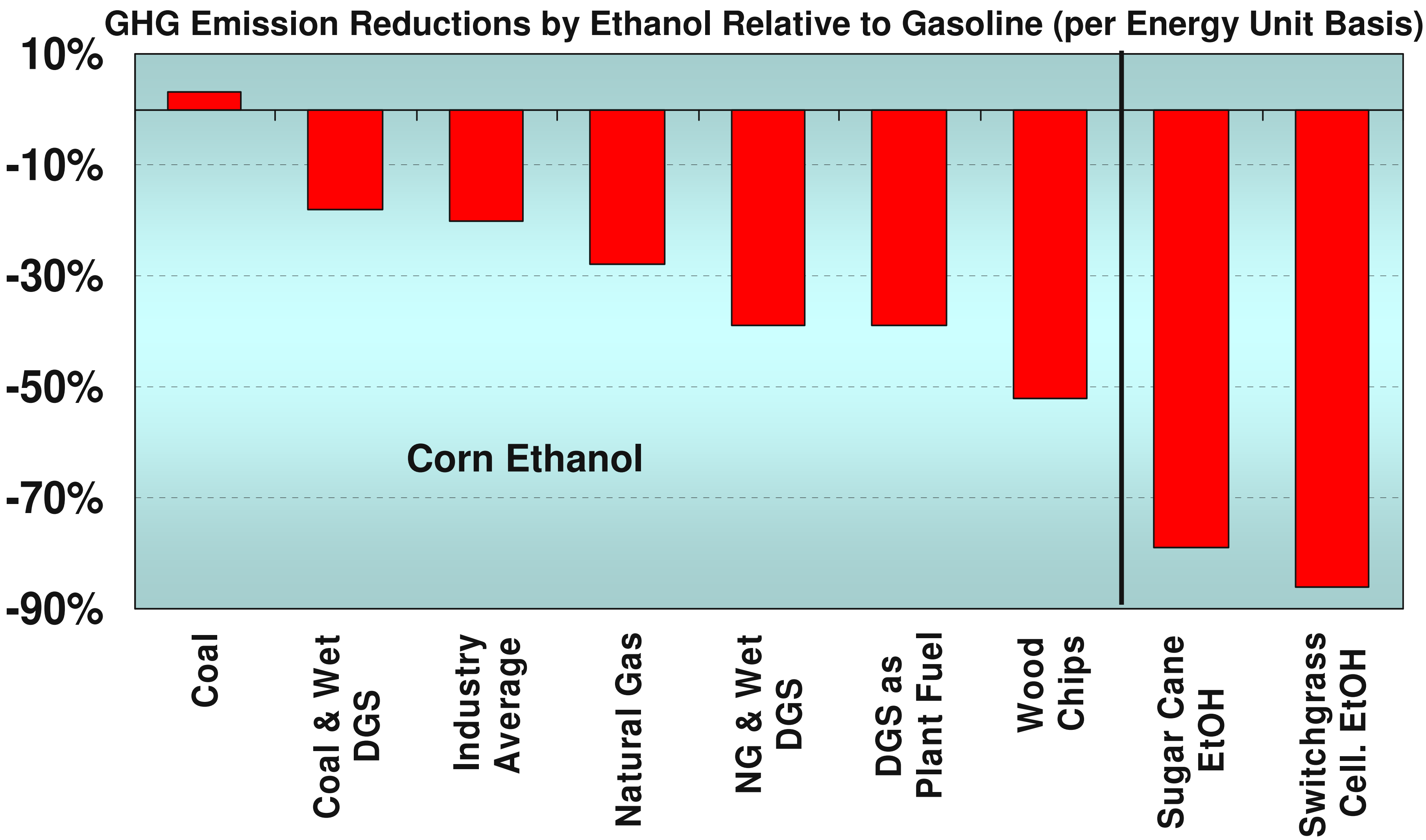
Based on historical USDA data; results are 3-year moving averages

Improved Technologies Have Reduced Energy Use and Operating Costs in Corn Ethanol Plants

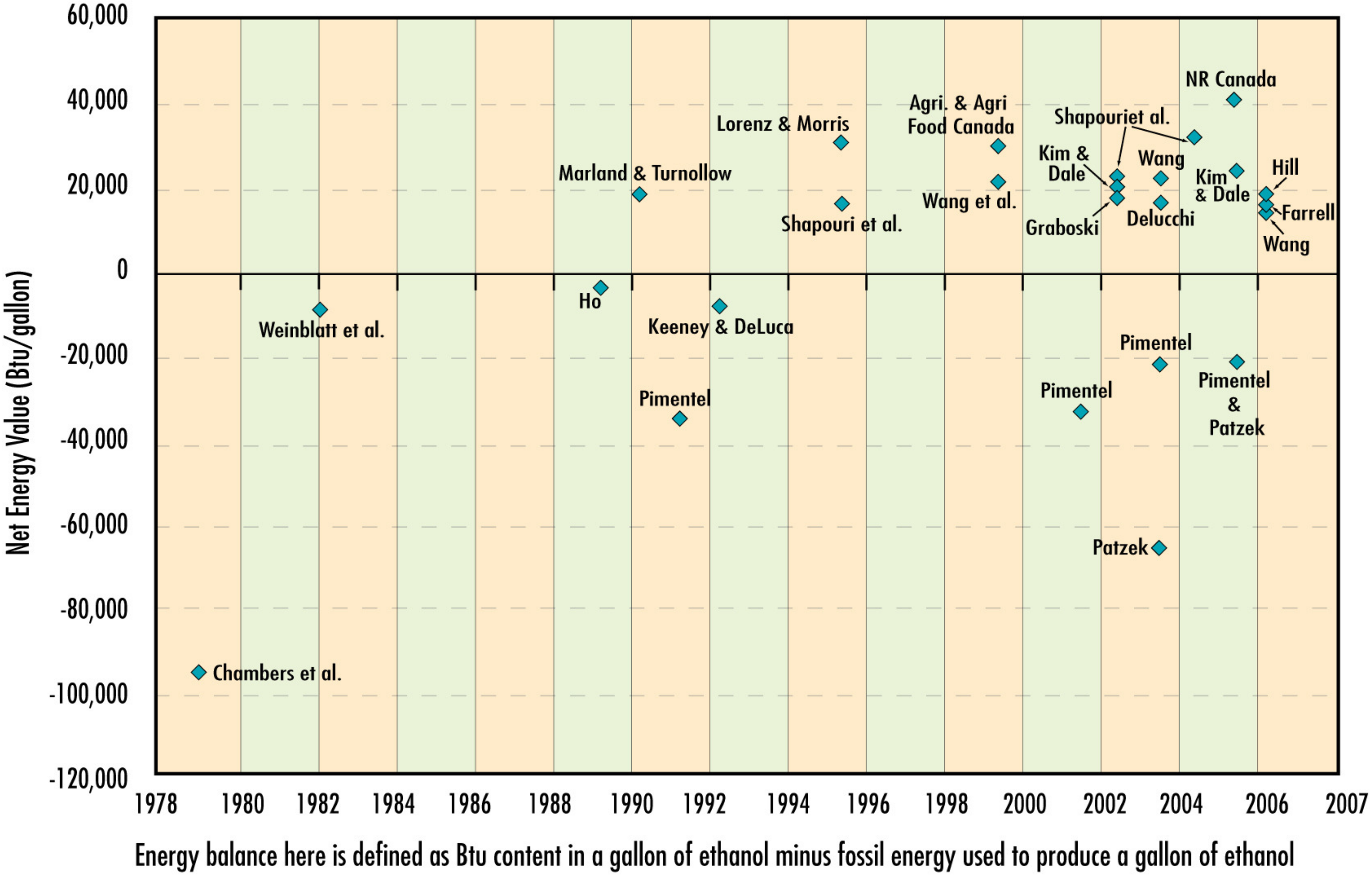


Data for new ethanol plants is from Mueller and Cuttica (2006)

From Corn to Sugar Cane to Cellulosic Biomass, Ethanol GHG Emission Reductions Are Increased



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

Co-Products with Biofuels

- Types of co-products
  - Corn ethanol: animal feeds (DGS)
  - Sugarcane ethanol: electricity
  - Cellulosic ethanol: electricity
  - Biodiesel and renewable diesel from soybean and rapeseed: animal feeds, glycerin, and other chemicals
- Ways of dealing with co-products
  - Displacement method (or the system boundary expansion approach)
  - Allocation methods
    - *Mass based*
    - *Energy content based*
    - *Economic revenue based*
  - Plant process purpose based
- Scale of biofuel production and resultant scale of co-product production affect the choice of methods

Accounting for Animal Feed Is a Critical Factor in Corn Ethanol's Lifecycle Analysis

Allocation Method	Wet milling	Dry milling
Weight	52%	51%
Energy content	43%	39%
Process energy	36%	41%
Market value	30%	24%
Displacement	~16%	~20%

Argonne uses the displacement method.

GREET Analysis Concluded That Energy Embedded in Farming Equipment Is Not a Significant Contributor to Ethanol's Life-Cycle Energy Use

- Size of farm
- Life time of equipment
- Energy for producing equipment materials (the majority of equipment materials is steel and rubber)
- Argonne has found that farming equipment may contribute to <2% of energy and ~1% GHG emissions for corn ethanol

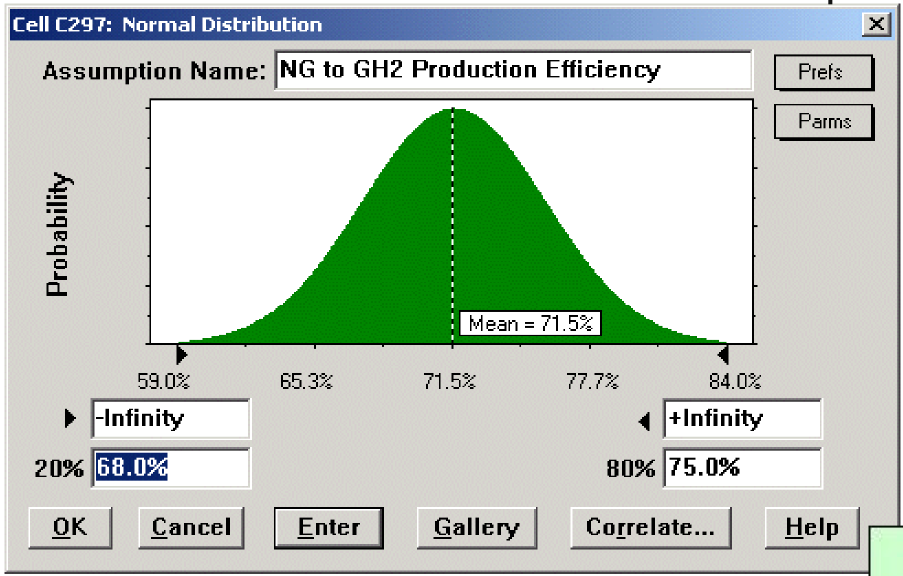
Equipment	Weight (tons)	Lifetime (yr)
Large tractor	10	15
Small tractor	5.7	15
Field cultivator	2.6	10
Chisel plow/ripper	4.0	10
Planter	3.7	10
Combine	13.7	15
Corn combine head	4.0	10
Gravity box (4)	7.3	15
Auger	0.9	10
Grain bin (3)	10.5	15
Irrigation	5.3	12
Sprayer	0.6	10

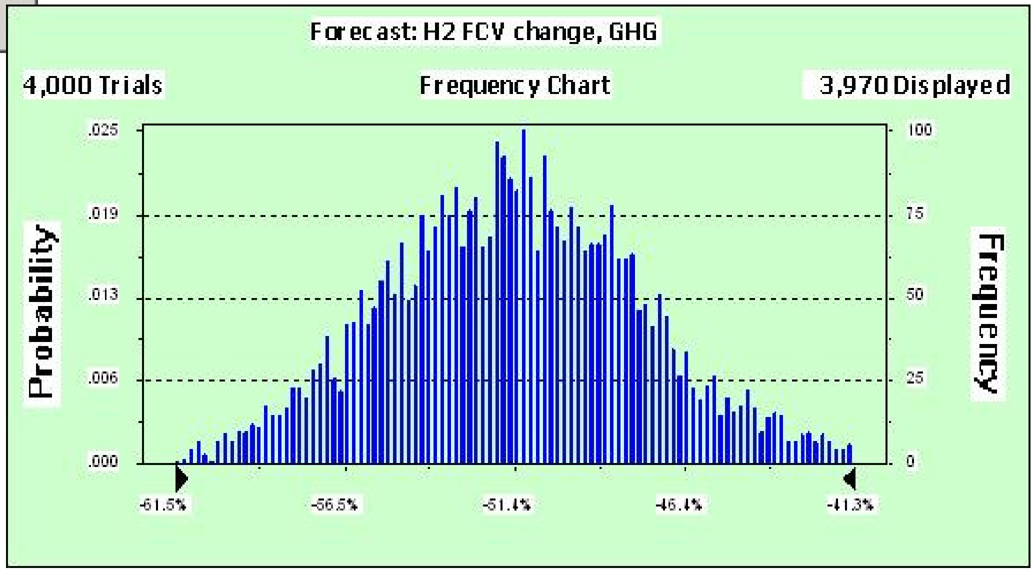
Potential Land Use Change by Large-Scale Biofuel Production Needs to Be Examined

- **Primary land use change and secondary land use change**: the latter is much more difficult to assess
- No comprehensive simulations of land use change at the national and global level have been done yet, especially for a biofuel future; agricultural community needs to be engaged in land use change modeling
- Soil carbon content and vegetation carbon content in different land use patterns
- U.S. annual corn ethanol production from 6 to 15 billion gallons in ten years by 2015
  - Besides increases in per-acre corn yield, where will additional amount of corn for ethanol production be from?
  - In 2007, U.S. corn farming acres have increased by 12 million through switch from soybean to corn farming
  - U.S. has been exporting 20% of its total annual corn production; reduction in U.S. corn export will impact global corn/grain market
- Brazil has 12.4 million acres of sugar cane plantations. It can increase sugar cane plantations to 25 million acres in the near future
  - While sugar cane farming is in South Central Brazil, what is the current farming practice and vegetation for the additional sugar cane acres?
  - Will the increase in sugar cane farming acres push farming of corn, soybean, and cattle to the Amazon rainforest region?
- Palm oil production in Malaysia has caused conversion of some tropical forest and pit soil into palm tree farming; what is the environmental and GHG consequences?

Uncertainties in LCAs May Need to Be Addressed Systematically

GREET Uses Distribution-Based Inputs to Generate Distribution-Based Outputs





Key Issues For Biofuel Life-Cycle Analyses

- Models should be (and usually are) in synchronization with GHG accounting and reduction protocols to become policy relevant
  - Though many pollutants (such as CO, NMOCs, NOx, SOx, PM, etc.) may impact climate change, the magnitude of their effects is unsettled
  - Analyses for helping GHG reduction **policy** designs need to be based on an accepted basis such as the IPCC protocol
- Key assumptions affecting GHG emission results, thus GHG policies/regulations, need to be thoroughly examined and verified
  - Technology advancement over time
  - Co-products
  - Land use changes
  - Carbon and N2O emissions from soil
  - Allocation of GHG emission credits and burdens among different countries and players
  - Consensus for key assumptions may be necessary for policy design purposes
- Global life-cycle analysis protocol and certification protocol for biofuels seem necessary to ensure sustainable development of biofuels