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# Well-to-Wheels Analysis of Biofuels and Plug-In Hybrids

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*Presentation at the Joint Meeting of*
*Chicago Section of American society of Agricultural and Biological Engineers*
*And Chicago Section of Society of Automotive Engineers*
*Argonne National Laboratory, June 3, 2009*

U.S. Department of Energy

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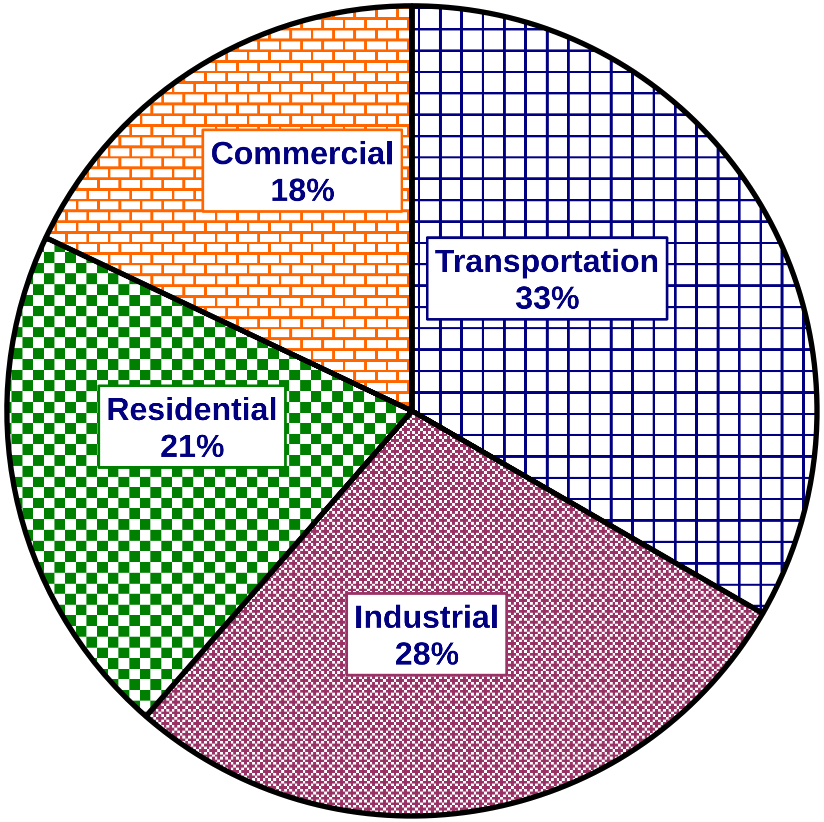
# *The Transportation Sector: Dual Challenges, Dual Approaches*

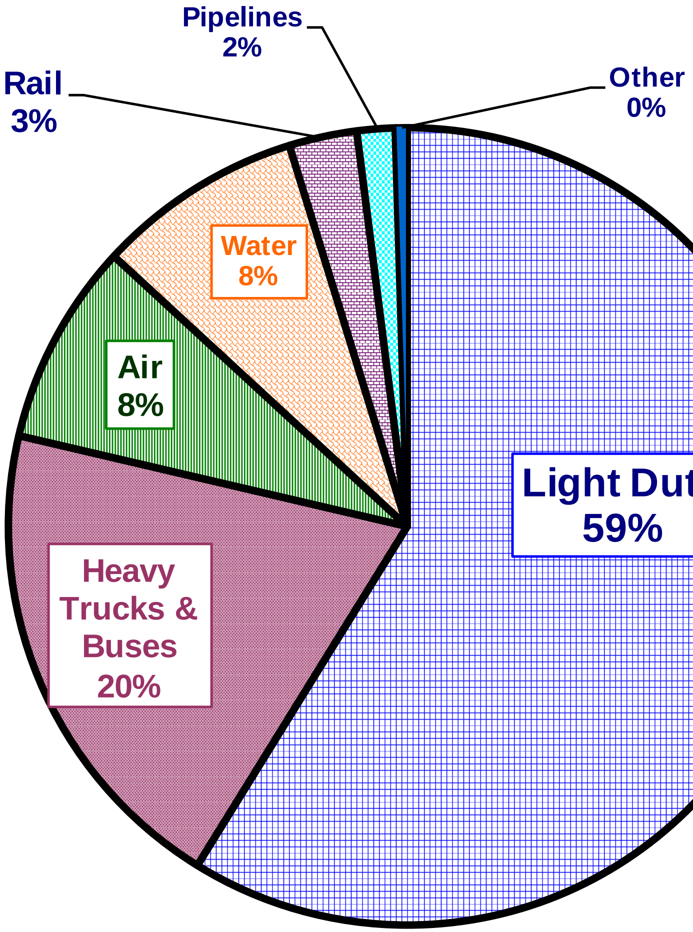
- Challenges
  - Greenhouse gas emissions – climate change
  - Oil use – energy security

- Approaches
  - Vehicle efficiency (and transportation system efficiency)
  - New transportation fuels

# US Greenhouse Gas Emission Shares by Source



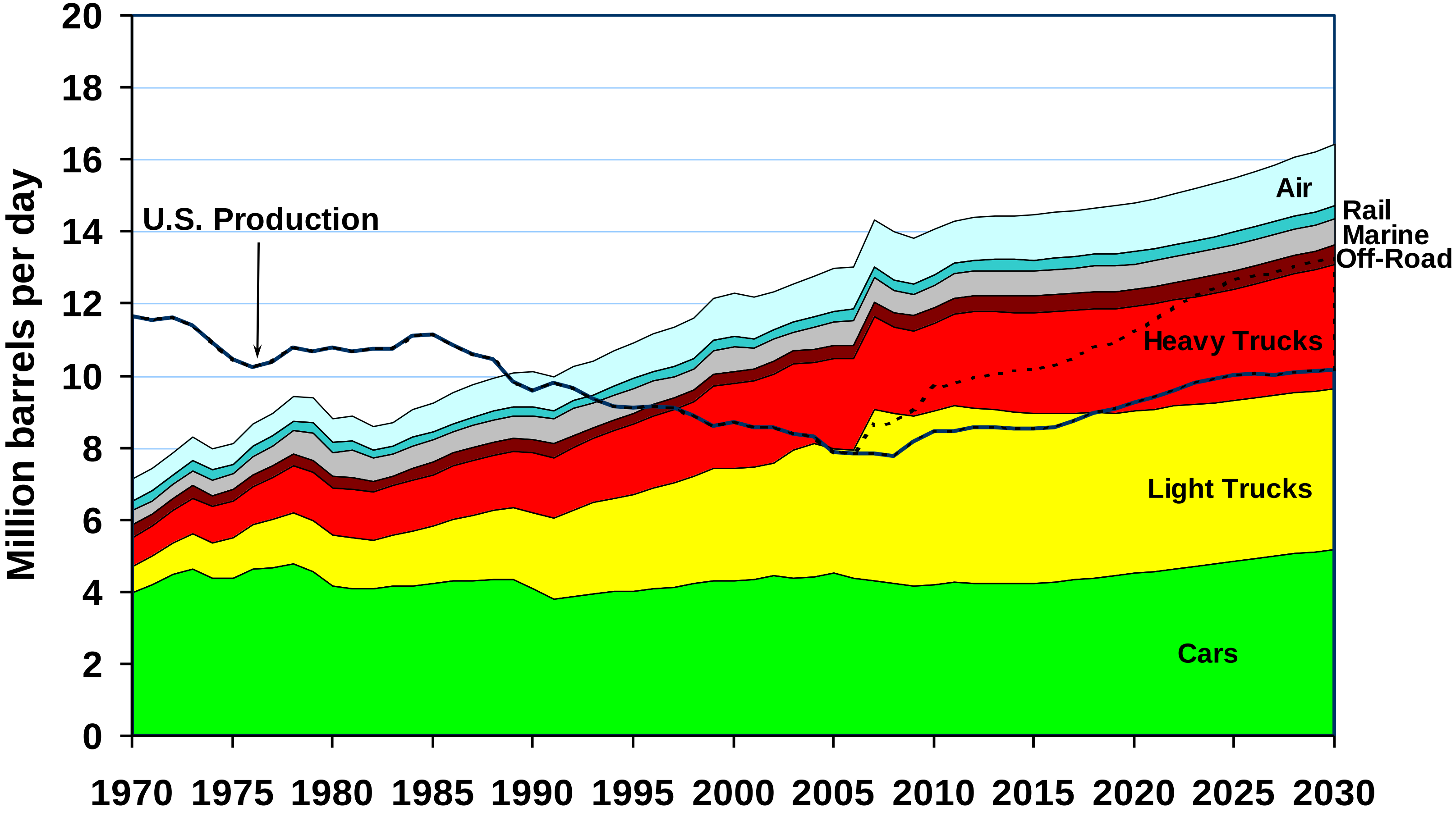

2006 GHG Emissions (CO2 Eqv)




2006 GHG Emissions (CO2 Eqv)

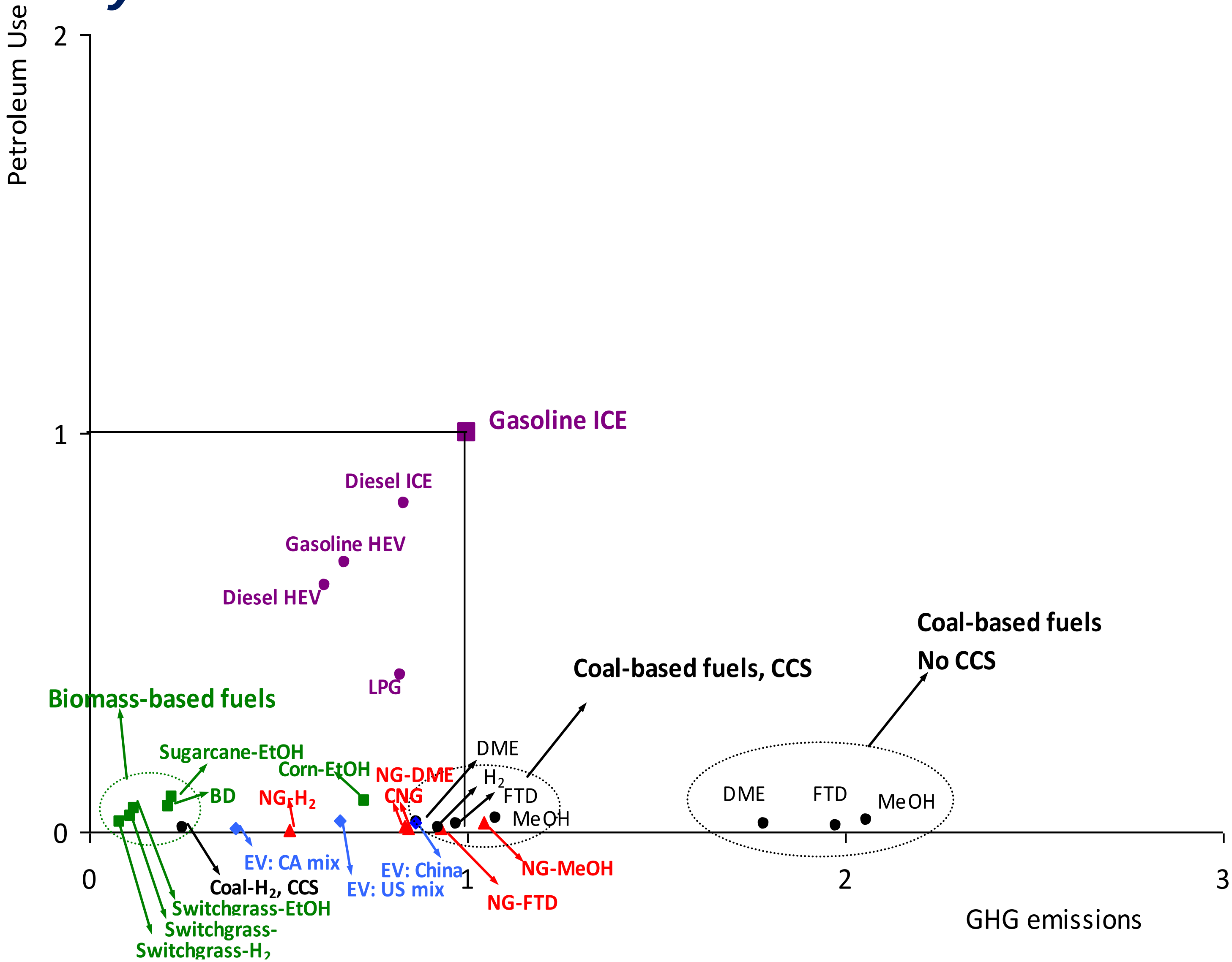
Annual US total GHG emissions are 5.6 GT of CO2e

# U.S. Petroleum Production and Consumption, 1970-2030




Sources: *Transportation Energy Data Book: Edition 27* and projections from the Early Release *Annual Energy Outlook 2009*.

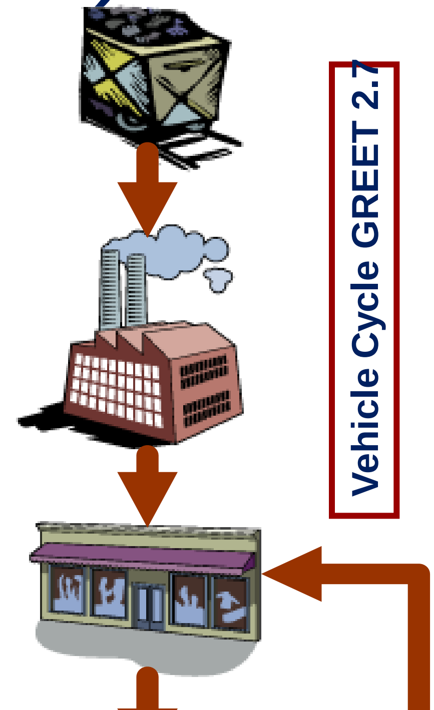
# Coal-Based Fuels Pose a Trade-Off Between Energy Security and GHG Emissions



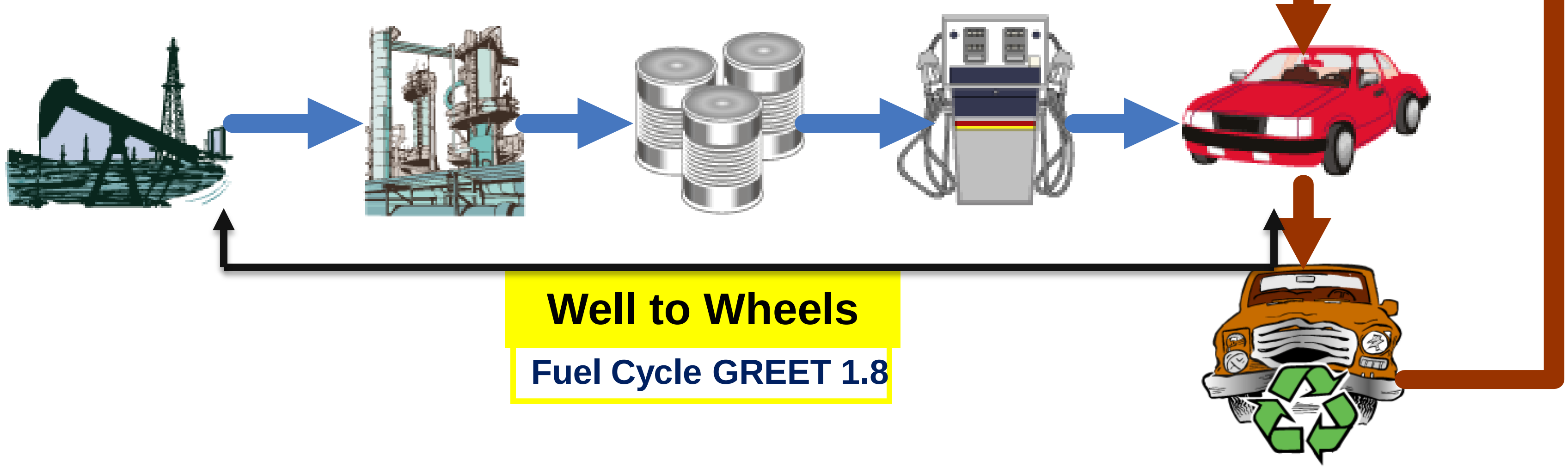
# *Life-Cycle Analysis for Vehicle/Fuel Systems Has Been Evolved in the Past 30 Years*

- Historically, evaluation of vehicle/fuel systems from wells to wheels (WTW) was called fuel-cycle analysis
- Pioneer transportation WTW analyses began in 1980s
  - Early studies were motivated primarily by battery-powered EVs
  - Recent studies were motivated primarily by introduction of new fuels such as hydrogen and biofuels
- Pursuing reductions in transportation GHG emissions now demands for intensive and extensive WTW analyses

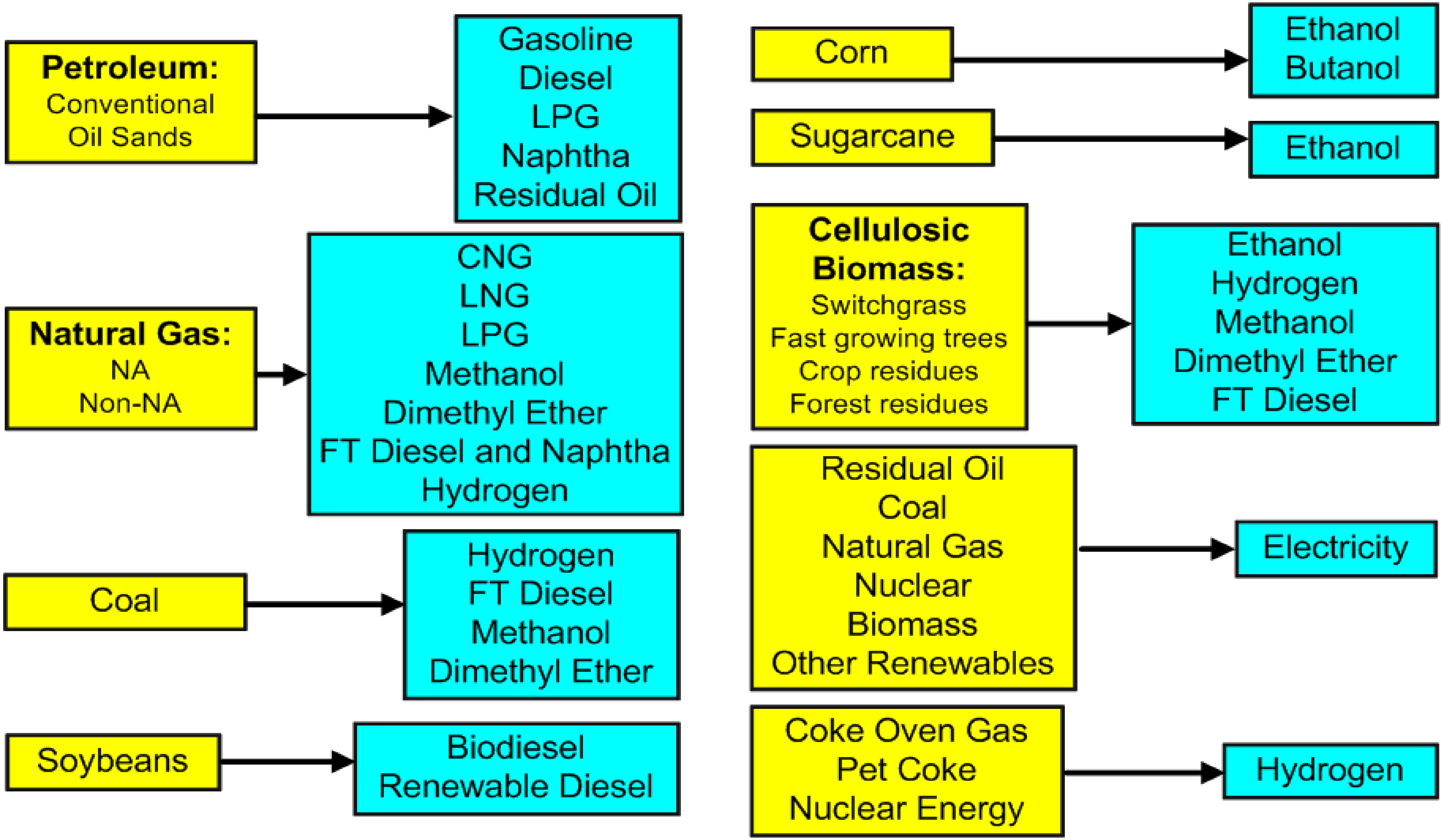
# *The GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) Model*




- **The GREET model and its documents are available at Argonne's website at *http://www.transportation.anl.gov/modeling_simulation/GREET/index.html***
- **The most recent GREET version (GREET 1.8c) was released in March 2009**
- **As of Jan. 2009, there were more than 10,000 registered GREET users worldwide**



# *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

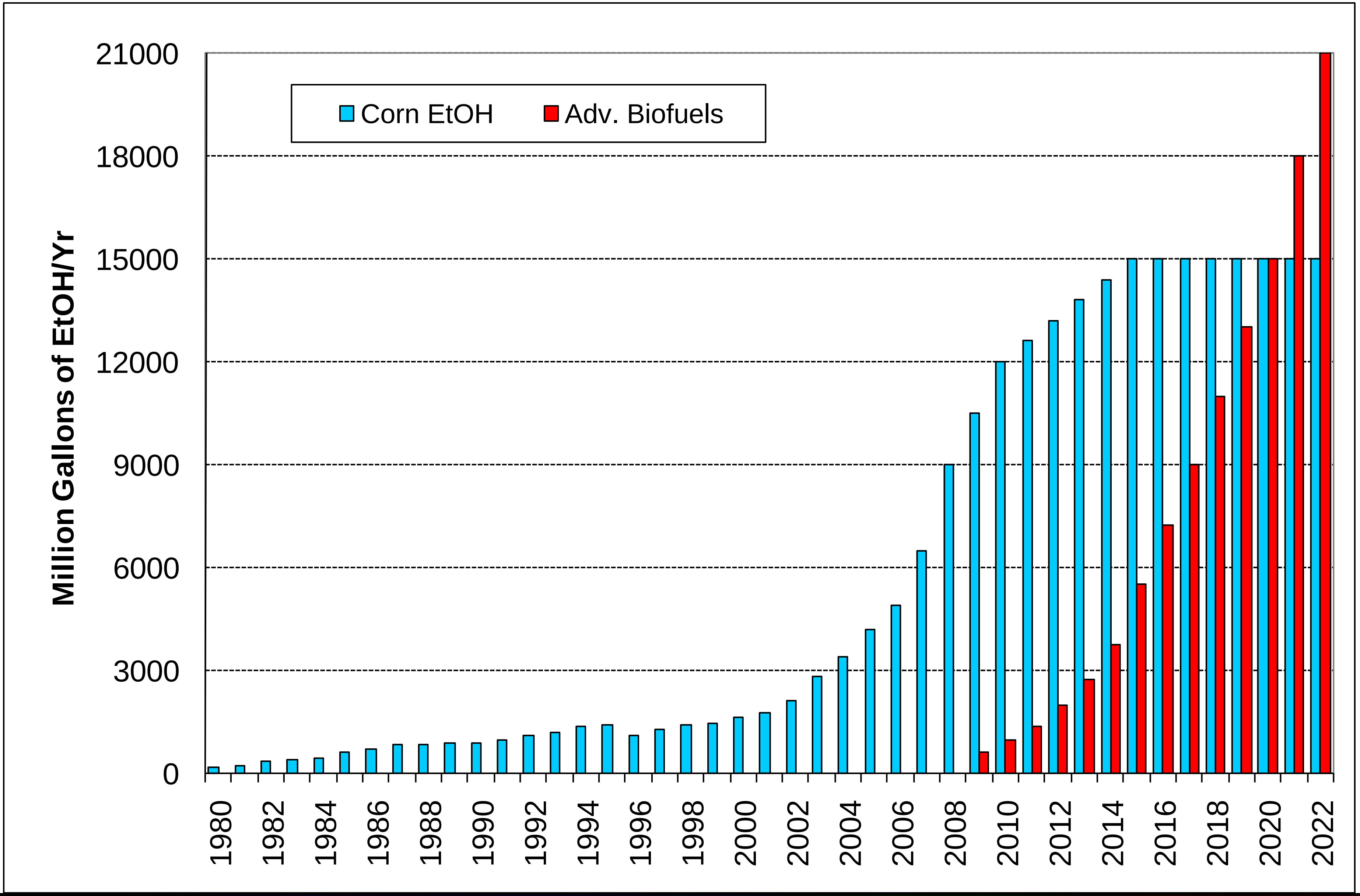
**Spark-Ignition Direct-Injection Vehicles**
- Conventional gasoline, federal reformulated gasoline, and California reformulated gasoline
- Methanol and ethanol

# GREET Includes Some of the Potential Biofuel Production Pathways

- Sugar Crops for EtOH
  - <u>**Sugar cane**</u>
  - Sugar beet
  - Sweet sorghum
- Starch Crops for EtOH
  - <u>**Corn**</u>
  - Wheat
  - Cassava
  - Sweet potato
- Algaes
  - Oils
  - Hydrogen
- 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.

# The 2007 Energy Independence and Security Act (EISA) Established Aggressive Biofuel Production Targets



# The 2007 EISA and Low-Carbon Fuel Standard Development Require Life-Cycle Analysis for Fuels

- EISA requires LCAs to be conducted to determine if given fuel types meet mandated minimum GHG reductions
  - New ethanol produced from corn: 20%
  - Cellulosic biofuels: 60%
  - Biomass-based diesel (e.g., biodiesel): 50%
  - Other advanced biofuels (e.g., imported sugarcane ethanol, renewable diesel, CNG/LNG made from biogas): 50%
  - EPA released a notice of proposed rulemaking (NPRM) in early May
- Low-carbon fuel standard development efforts in EU, California, and other states require LCAs for biofuels
- Life cycle analysis includes
  - All major GHGs ($CO_2$, $CH_4$, and $N_2O$)
  - Both production and use of fuels
  - Direct and indirect land use change impacts

# *California Has Adopted Low-Carbon Fuel Standards (LCFS) in April 2009*

- 10% reduction in carbon intensity of CA fuel supply pool (in g CO2e/MJ) by 2020
- GREET was used to develop fuel-specific carbon intensities
- Purdue's GTAP model was used for land use simulations
- Fuel carbon intensity may be adjusted with vehicle efficiency

**Adopted Carbon Intensities for Selected Fuels (g CO2e/MJ)**

| Fuel | Direct Emissions | Land Use or other effects | Total |
|---|---|---|---|
| CA Gasoline | 95.86 | 0 | 95.86 |
| Midwest Corn EtOH | 69.40 | 30 | 99.40 |
| CA Corn EtOH, wet DGS | 50.70 | 30 | 80.70 |
| Sugarcane EtOH | 27.40 | 46 | 73.40 |
| CA Electricity | 124.10 | 0 | 41.37 |
| NG-Based H2 | 142.20 | 0 | 61.83 |

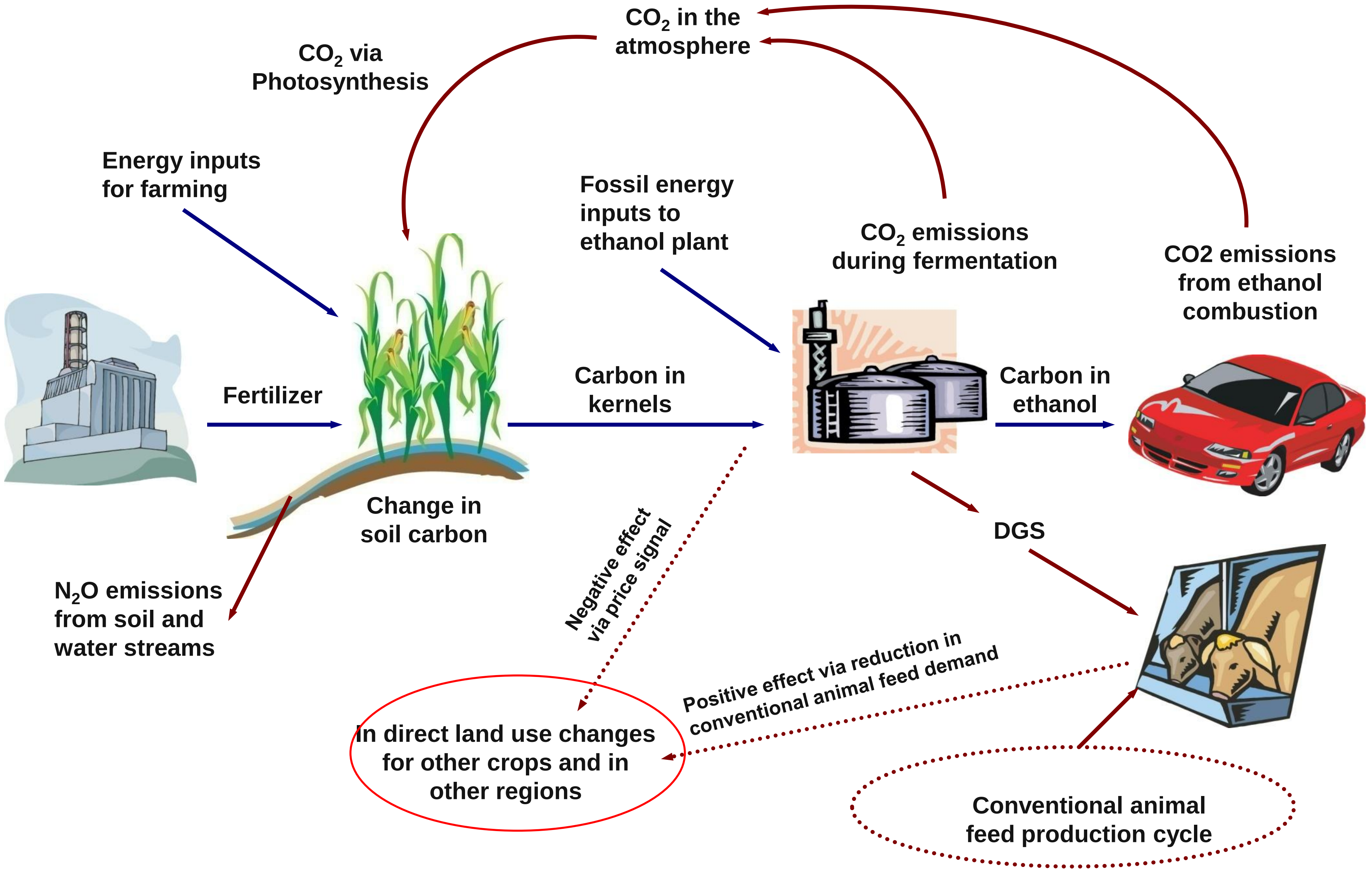
# *The U.S. EPA Released A Notice of Proposed Rulemaking (NPRM) for EISA RFS2 in May 2009*

- A suite of models (including GREET) were used to conduct biofuel LCAs
- Land use change in EPA's NPRM, as well as in CA's LCFS, has been a contentious issue

**EPA Estimated Biofuel GHG Changes (Relative to 2005 Gasoline)**

| | 100 yr, 2% Discount | 30 yr, 0% discount | EISA Target |
|---|---|---|---|
| Corn EtOH | -16% | +5% | **-20%** |
| Sugarcane EtOH | -44% | -26% | **-50%** |
| Corn Stover EtOH | -115% | -117% | **-60%** |
| Switchgrass EtOH | -128% | -121% | **-60%** |
| Soybean Biodiesel | -22% | +4% | **-50%** |
| Waste Grease Biodiesel | -80% | -80% | **-50%** |

# GHG Benefits and Burdens for Fuel Ethanol Cycle Occur at Different Stages (and With Different Players)



# *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
  - Distillers grains and solubles (DGS) for corn ethanol: 0-50%
  - Electricity for cellulosic and sugarcane ethanol
  - Animal feed and specialty chemicals for biodiesel
- Life-cycle analysis methodologies
  - Attributional LCA: CA LCFS
  - Consequential LCA: EPA RFS2
- Direct and indirect land use changes and resulted GHG emissions

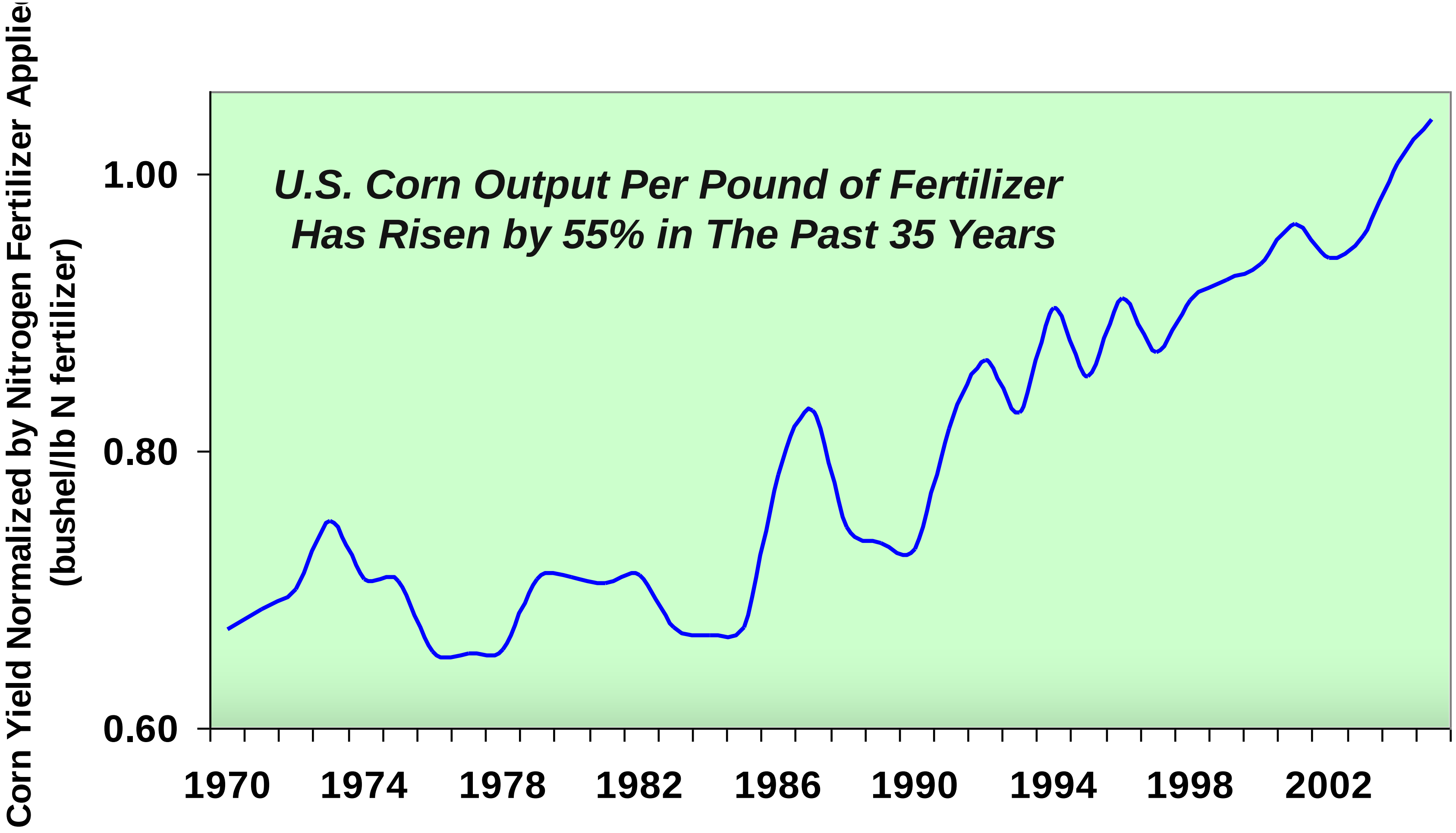
# *Key Steps to Address GHG Emissions of Potential Land Use Changes by Large-Scale Biofuel Production*

- Simulations of potential land use changes
  - So far, general equilibrium models have been used
    - ✓ CA LCFS: Purdue GTAP
    - ✓ EPA RFS2: Texas A&M FASOM and Iowa State FAPRI
  - Significant efforts have been made in the past 16 months to improve existing CGE models
  - More efforts may still be required
- 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 Century model) but others are very aggregate (e.g., IPCC)
  - There are mismatches between simulated land types and the land types in available carbon databases
  - Soil depth for soil carbon could be a major issues when energy crops are to be simulated

# *Specific Issues with General Equilibrium Modeling of Land Use Changes by Biofuel Production*

- Baseline definition
  - Understanding of the issue has been advanced
  - Definition itself may still not be agreed; scenarios may be the way to go
- Worldwide land availability and productivity
- Growth of crop yields
  - Trend yield growth
  - Yield growth response to price increase
  - Two key technical parameters to predict yields: price elasticities; land rent (or other parameter)
- Various worldwide biofuel programs: are they parts of a biofuel system or competing individual programs?
- How to value animal feeds in modeling?
  - Nutrition value vs. market price approach
  - Advancement has been made; reconciliation between the two approaches is still needed

# *Accurate Ethanol Energy Analysis Must Account for Increased Productivity in Farming Over Time*



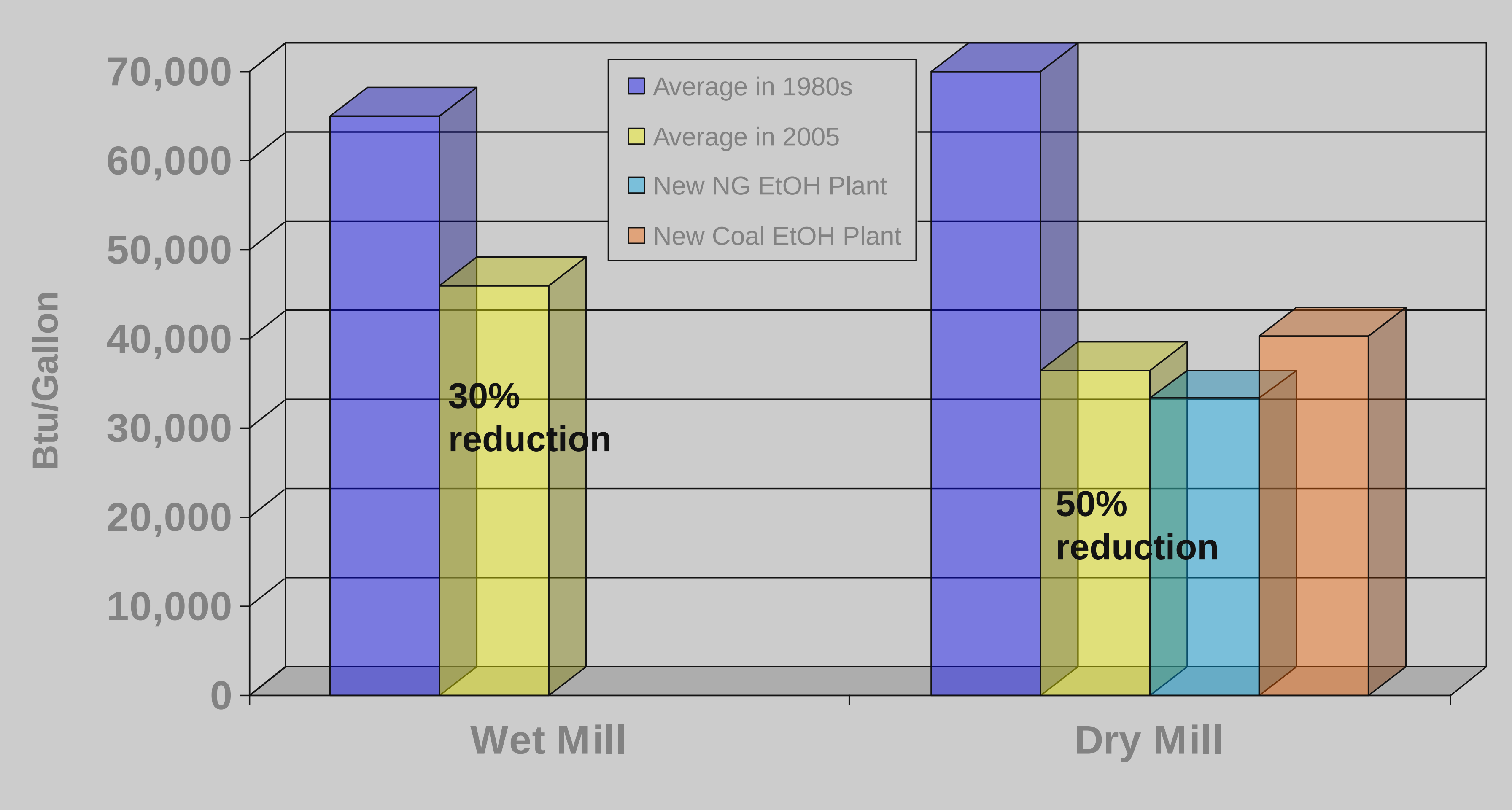

**Based on harvested acreage. Source: USDA**

# GREET Includes Building of Farming Equipment for Ethanol WTW Analysis

- Size of farm served by equipment
- Life time of equipment
- Energy for producing equipment materials (the majority of equipment materials is steel and rubber)
- Argonne has found that building of 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 |

# *Improved Technology and Plant Design Has Reduced Energy Use and Operating Costs in Corn Ethanol Plants*

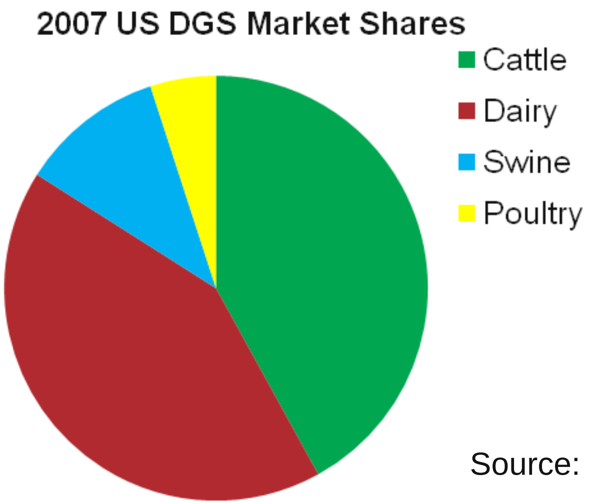


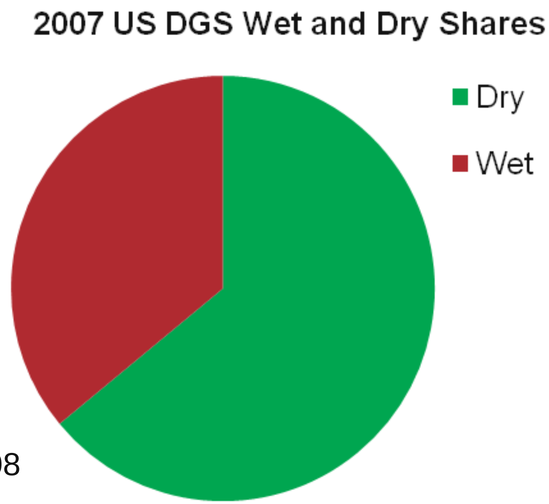

There are indications that the ethanol industry continues to reduce plant energy use.

# Co-Products with Biofuels

- Types of co-products
  - Corn ethanol: animal feeds (distillers grains and solubles, 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
  - Production plant process purpose based
- Scale of biofuel production (and resultant scale of co-product production) can affect the choice of methods

# Proper Accounting for Animal Feed Is Key to Corn Ethanol WTW Analysis



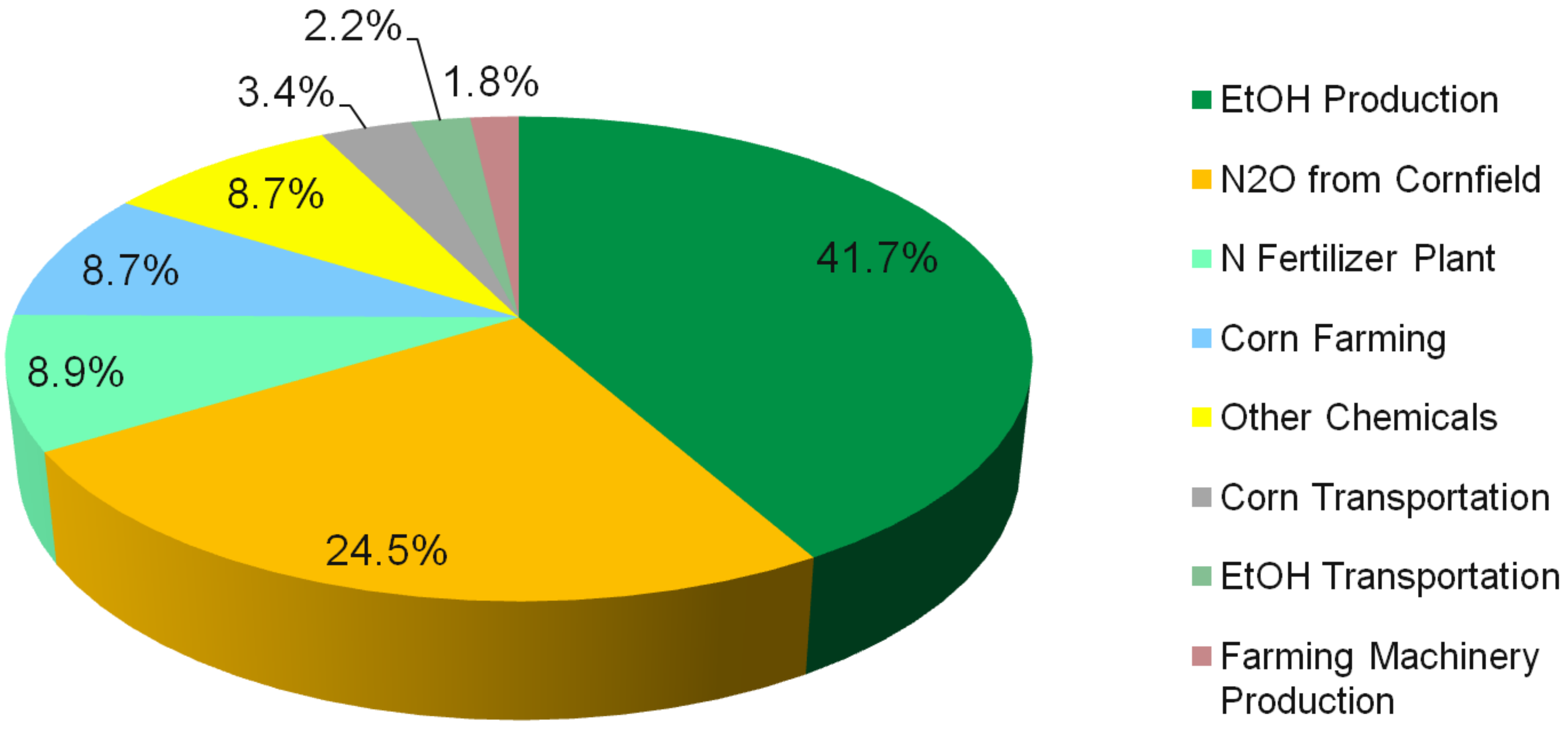




Source: RFA, 2008

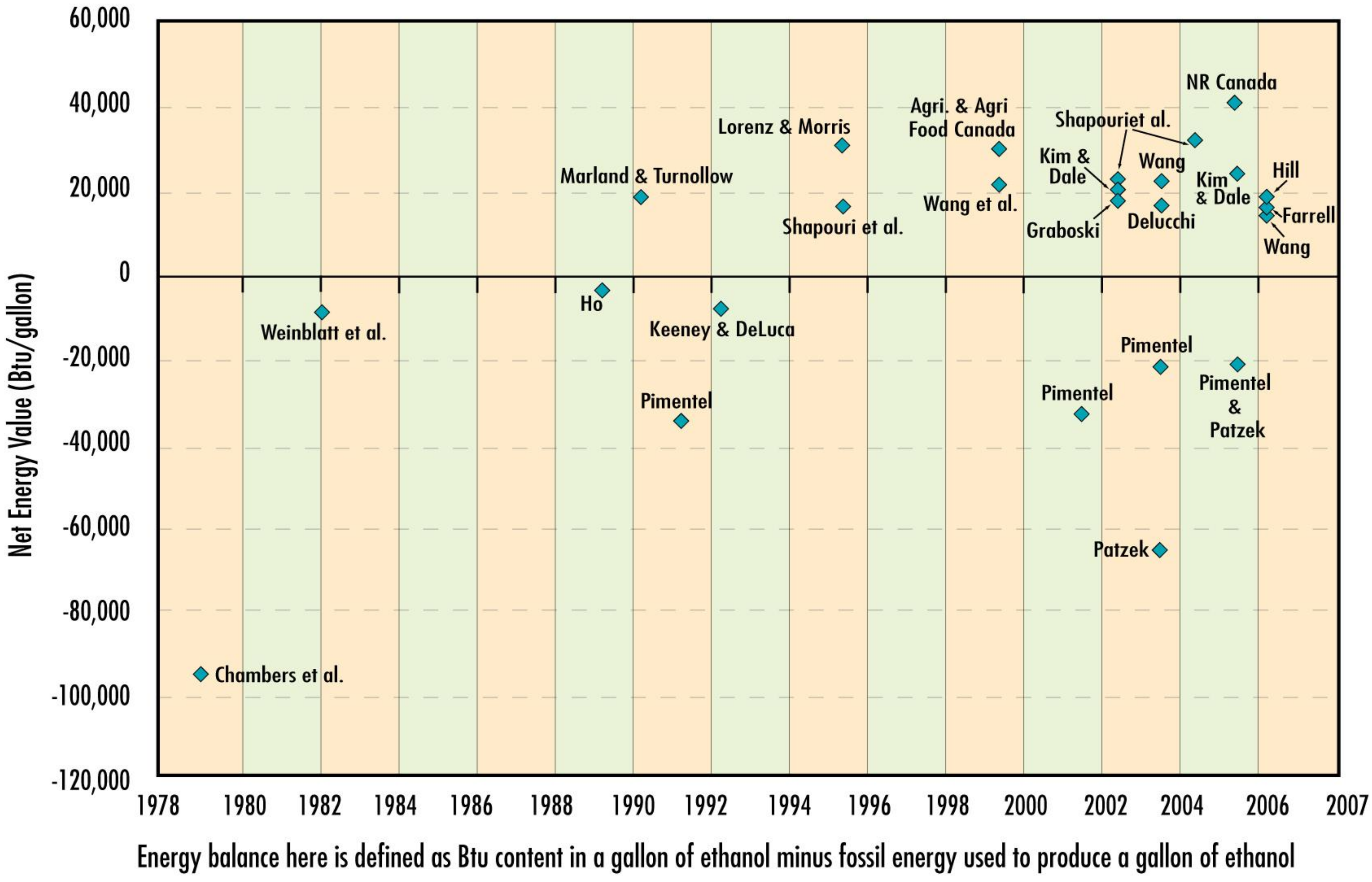
| Allocation Method | GHG to EtOH | GHG to GDS |
|---|---|---|
| Weight | 54% | 46% |
| Energy content | 62% | 38% |
| Process energy | 68% | 32% |
| Market value | 77% | 23% |
| Displacement | 81% | 19% |

Argonne uses the displacement method, the most conservative method for ethanol evaluation.

# Share of GHG Emissions for Corn Ethanol (total of 5,630 g/gal, with co-product credits)



# Most Recent Studies Show Positive Net Energy Balance for Corn Ethanol

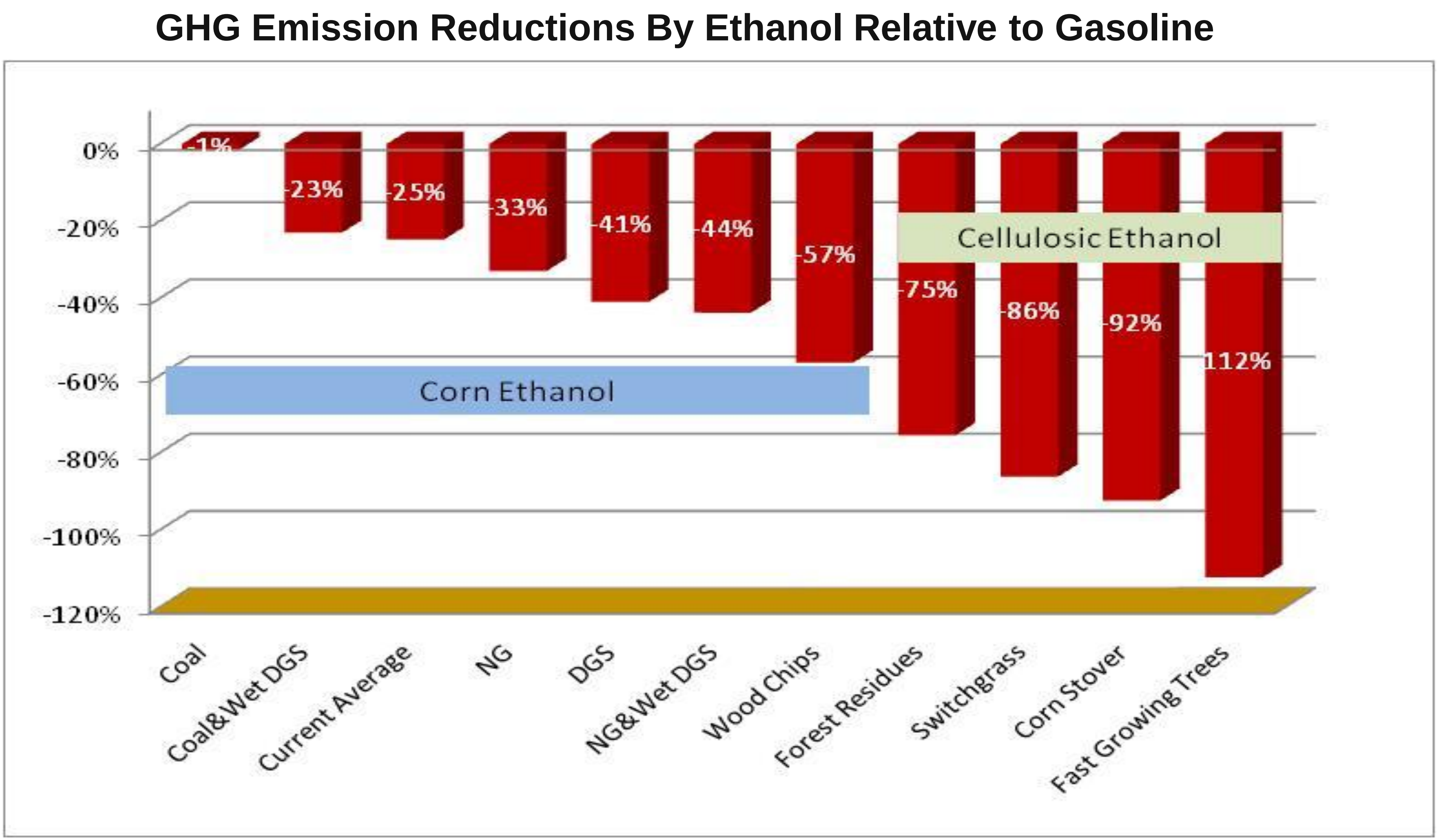



Energy balance here is defined as Btu content a gallon of ethanol minus fossil energy used to produce a gallon of ethanol

# *Key Issues Affecting Cellulosic Ethanol Results*

- Cellulosic biomass feedstock types
  - Fast growing trees
    - Soil carbon could increase
    - Fertilizer may be applied
    - Irrigation to be needed?
  - Switchgrass and other native grass
    - Soil carbon could increase
    - Fertilizer will be applied
    - Irrigation to be needed?
  - Crop residues
    - Soil carbon could decrease
    - Additional fertilizer will be needed to supplement nutrient removal
  - Forest wood residues: collection effort could be extensive
- Co-production of ethanol and electricity
  - The amount of electricity produced
  - The types of conventional electric generation to be displaced
- Land use changes could have less effects on cellulosic ethanol's GHG results

# GHG Emissions of Corn Ethanol Vary Considerably Among Process Fuels in Plants




GHG effects of potential land use changes are not fully included in these results.

# *Scope of Argonne's Plug-in Hybrid Electric Vehicle (PHEV) WTW Analysis*

- To examine relative energy and emission impacts of PHEVs; the vehicle types addressed were:
  - Conventional international combustion engine vehicles (ICEVs)
  - Regular hybrid electric vehicles (HEVs)
  - ICE plug-in hybrid electric vehicles (PHEVs)
  - Fuel cell (FC) PHEVs

- Fuel options:
  - Petroleum
    - ✓ Gasoline
    - ✓ Diesel
  - E85 with ethanol from
    - ✓ Corn
    - ✓ Switchgrass
  - Hydrogen with several production pathways
  - Electricity with different generation mixes

# Argonne's PHEV WTW Analysis Addresses The Following Key Issues

- PHEV performance evaluation with Argonne's PSAT model
  - Explored PHEV operating strategies
  - Processed fuel economy results for various PHEV configurations
  - Examined effects of all electric ranges (AER) of PHEVs
- PHEV mileage shares by power source
  - Relied on national average distribution of daily vehicle miles traveled (VMT)
  - Determined VMT shares by charge depleting (CD) and charge sustaining (CS) operations for PHEVs with different AERs
- Electricity generation mixes to charge PHEVs
  - Reviewed studies completed in this area
  - Generated five sets of generation mixes for PHEV recharge
- GREET WTW simulations of PHEVs
  - Expanded and configured GREET for PHEVs
  - Conducted GREET PHEV WTW simulations

# *Five Sets of Generation Mixes for PHEV Recharge Were Used in This Study (%)*

| Mix | Coal | Oil | Natural Gas | Nuclear | Other |
|---|---|---|---|---|---|
| US Average | 52.5 | 1.3 | 13.5 | 20.1 | 12.6 |
| Illinois – Region 4 (MAIN) Marginal | 75.2 | 0.0 | 24.7 | 0.0 | 0.1 |
| New York – Region 6 (NPCC-NY) Marginal | 3.4 | 67.2 | 29.4 | 0.0 | 0.0 |
| California – Region 13 (WECC-CA) Marginal | 0.0 | 0.0 | 99.0 | 0.0 | 1.0 |
| Renewable | 0.0 | 0.0 | 0.0 | 0.0 | 100.0 |

- US Average Mix: the default GREET average mix for 2020
- IL, NY, and CA Marginal Mix: from the 2020 mix with 2kW charging capacity starting at 10 PM from a study by Hadley et al.
- Renewable: a scenario reflecting upper limit on benefits of PHEVs

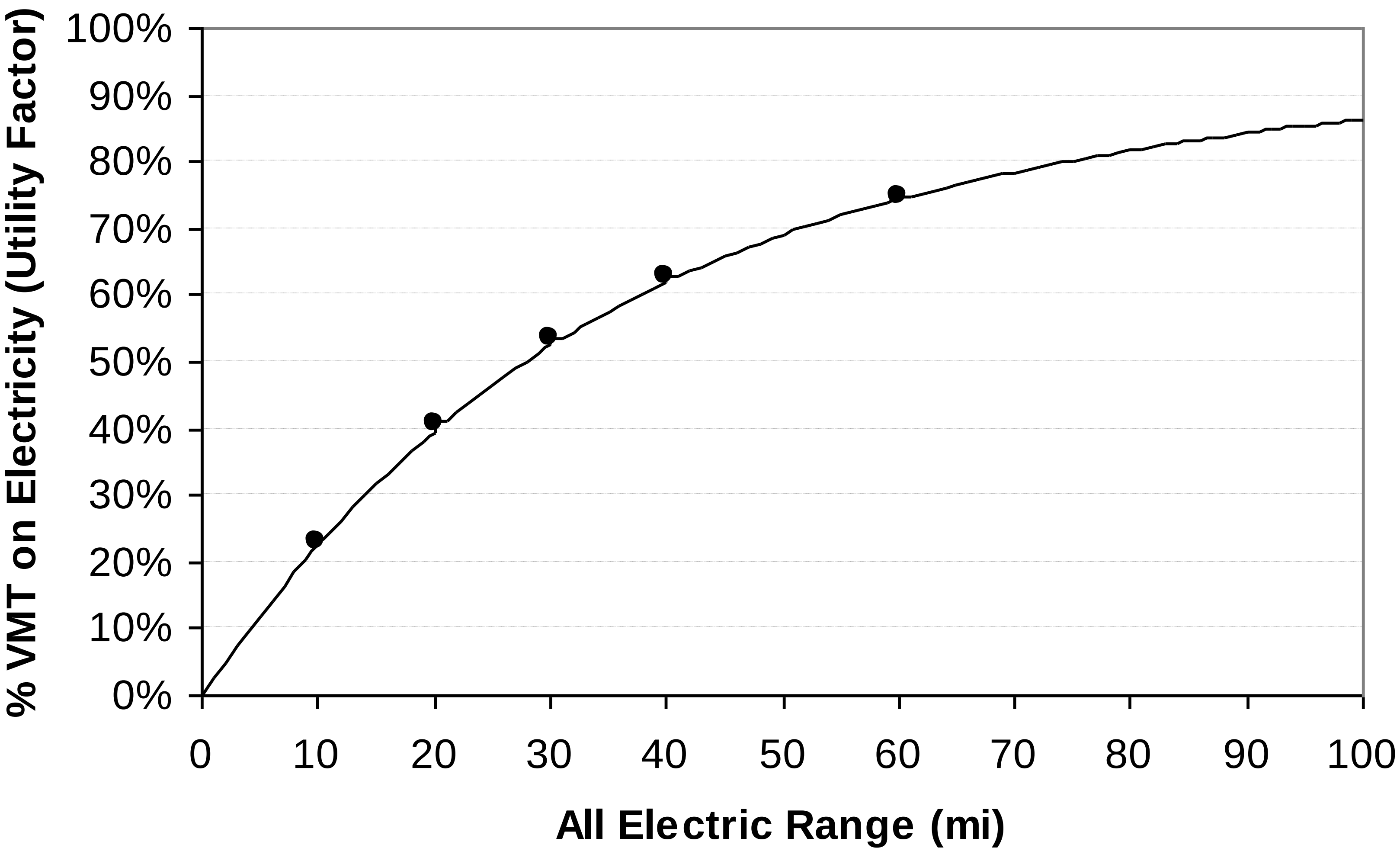
# PSAT Fuel Economy Results (Miles Per Gasoline Equivalent Gallon for CD Engine and CS Engine; Wh/Mile for CD Electric)

| | | ICEV | AER 0 | AER 10 | | | AER 20 | | | AER 30 | | | AER 40 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Regular Hybrid | CD Electric | CD Engine | CS Engine | CD Electric | CD Engine | CS Engine | CD Electric | CD Engine | CS Engine | CD Electric | CD Engine | CS Engine |
| Gasoline ICE | UDDS | 27.6 | 45.6 | 148.1 | 132.4 | 47.1 | 141.3 | 122.3 | 46.9 | 174.1 | 184.3 | 46.6 | 165.1 | 153.4 | 46.2 |
| | HWFET | 34.0 | 39.7 | 107.8 | 78.3 | 41.1 | 136.9 | 103.9 | 41.0 | 158.2 | 134.5 | 40.6 | 168.0 | 152.6 | 40.2 |
| E85 ICE | UDDS | | 42.9 | 146.1 | 125.5 | 44.4 | 141.2 | 118.4 | 44.2 | 172.6 | 179.7 | 43.8 | 164.3 | 148.6 | 43.4 |
| | HWFET | | 37.5 | 106.3 | 73.8 | 38.9 | 136.9 | 99.3 | 38.8 | 156.8 | 126.2 | 38.3 | 167.0 | 144.4 | 37.9 |
| Diesel ICE | UDDS | | 49.4 | 151.4 | 138.1 | 50.0 | 144.7 | 127.5 | 49.7 | 179.7 | 191.3 | 49.3 | 169.7 | 158.7 | 48.9 |
| | HWFET | | 43.0 | 110.2 | 84.1 | 43.8 | 140.3 | 112.2 | 43.6 | 163.3 | 145.7 | 43.2 | 172.6 | 164.5 | 42.9 |
| $H_2$ FC | UDDS | | 59.4 | 157.7 | 132.6 | 59.5 | 154.2 | 123.4 | 58.8 | 156.2 | 120.7 | 58.1 | 181.8 | 142.7 | 57.3 |
| | HWFET | | 62.3 | 229.4 | 1514.4 | 61.5 | 224.0 | 601.5 | 60.9 | 170.1 | 189.6 | 60.3 | 184.7 | 225.4 | 59.7 |

**CD electric operation and CD engine operation complement each other for the same CD miles (i.e., blended mode operation)**

- CD Electric = charge depleting operation with grid electricity
- CD Engine = charging depleting operation with on-board power systems (ICE or Fuel Cell)
- CS engine = charge sustaining operation with on-board power systems
- AER 0 = zero-mile AER (i.e., regular HEV)
- AER 10 = 10-mile AER; AER 20 = 20-mile AER; AER 30 = 30-mile AER; AER 40 = 40-mile AER
- UDDS = Urban Dynamometer Driving Schedule; HWFET = Highway Fuel Economy Test

# *PHEVs with 20-Mile AER Can Potentially Drive 40% of Daily VMT with CD Operation, PHEVs with 40-Mile AER More than 60%*

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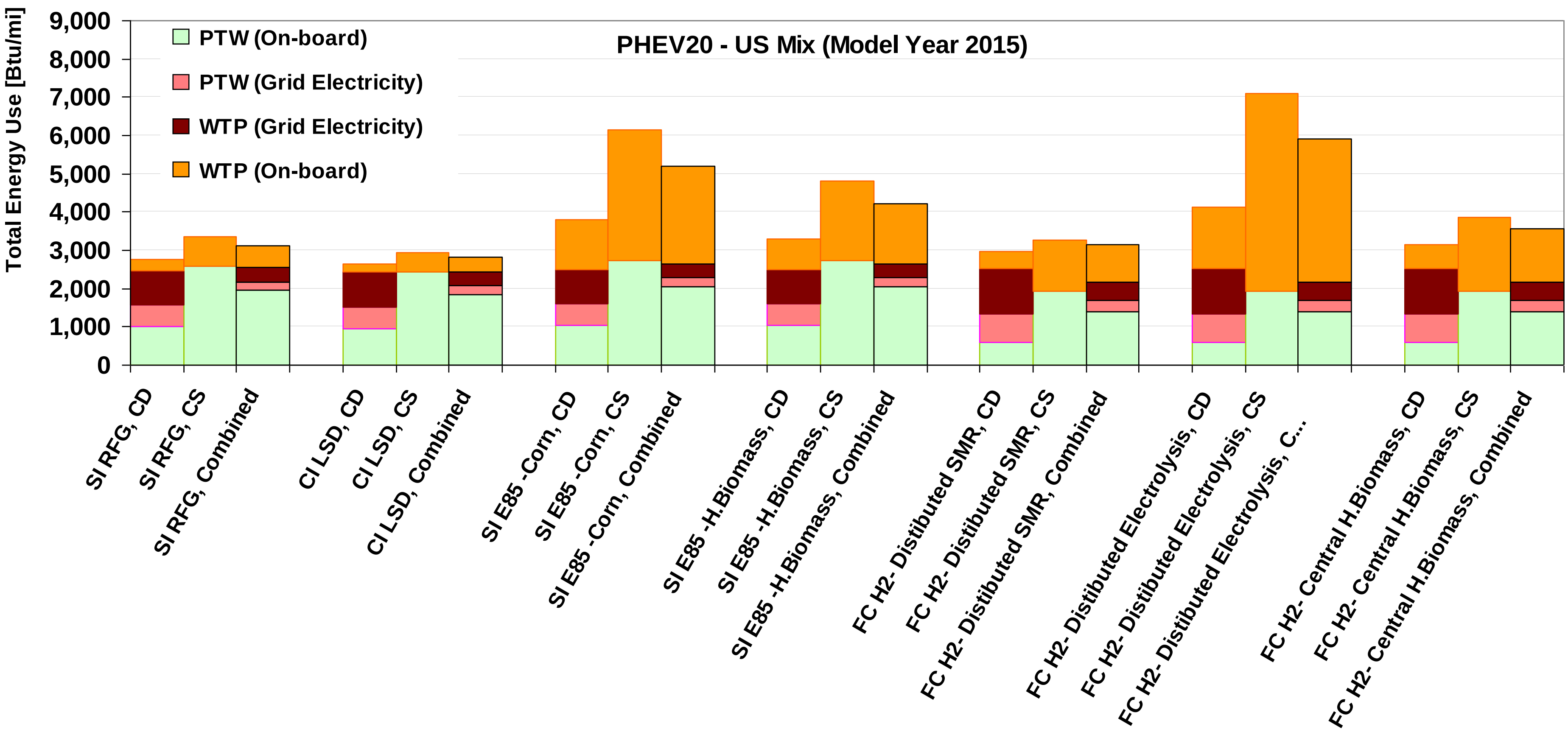
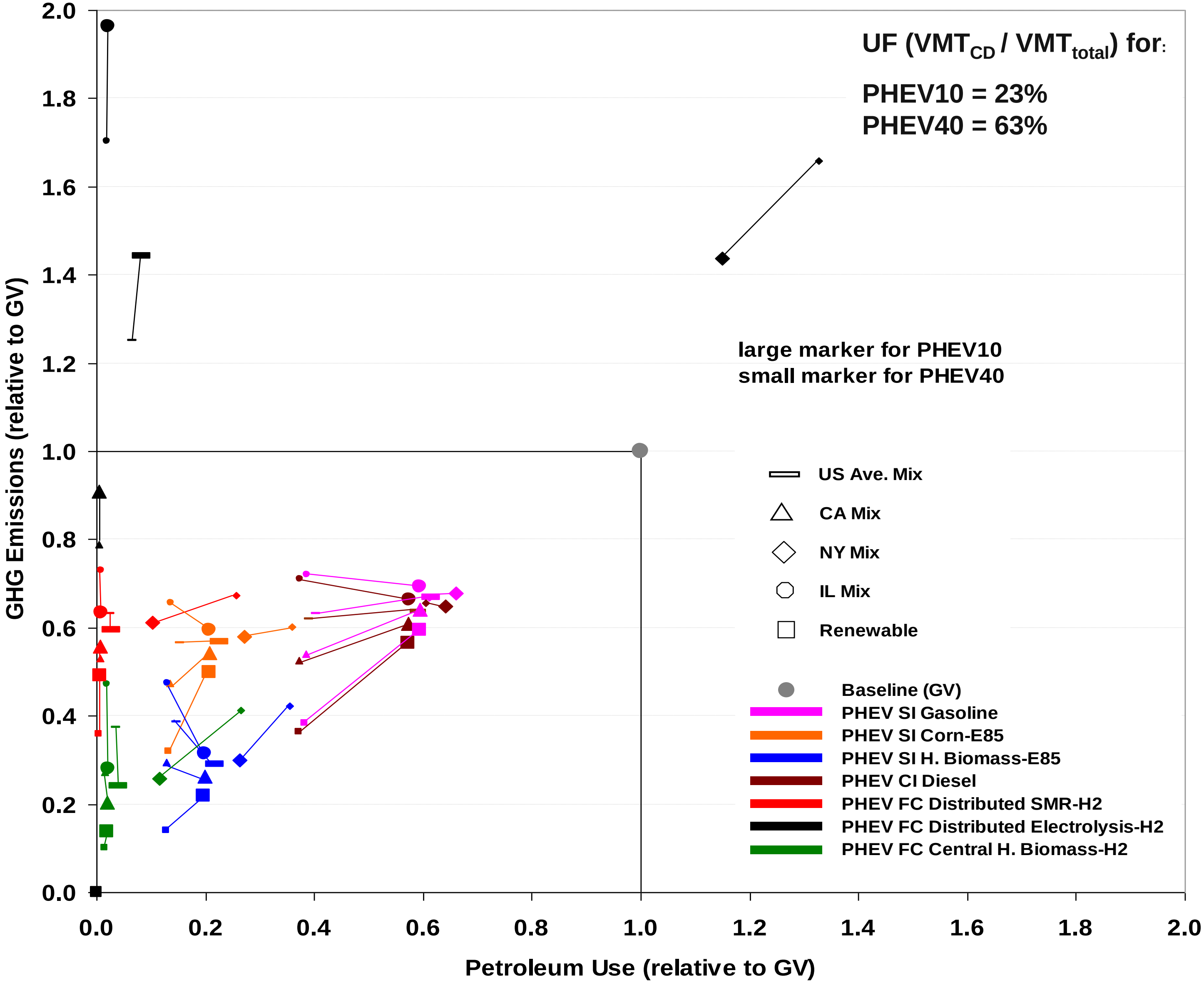
# *WTW <u>Total Energy Use</u> for CD Mode vs. CS Mode vs. Combination; 20 AER; US Mix*




The combination of CD and CS modes are with 40% CD VMT and 60% CS VMT.

# Summary of Petroleum Energy and GHG Effects of Evaluated PHEV Options



# Summary of Petroleum Energy and GHG Effects of Favorable Options