# Life-Cycle Analysis of Vehicle/Fuel Systems with the GREET Model

Michael Wang （王全录）
Systems Assessment Group
Energy Systems Division
Argonne National Laboratory

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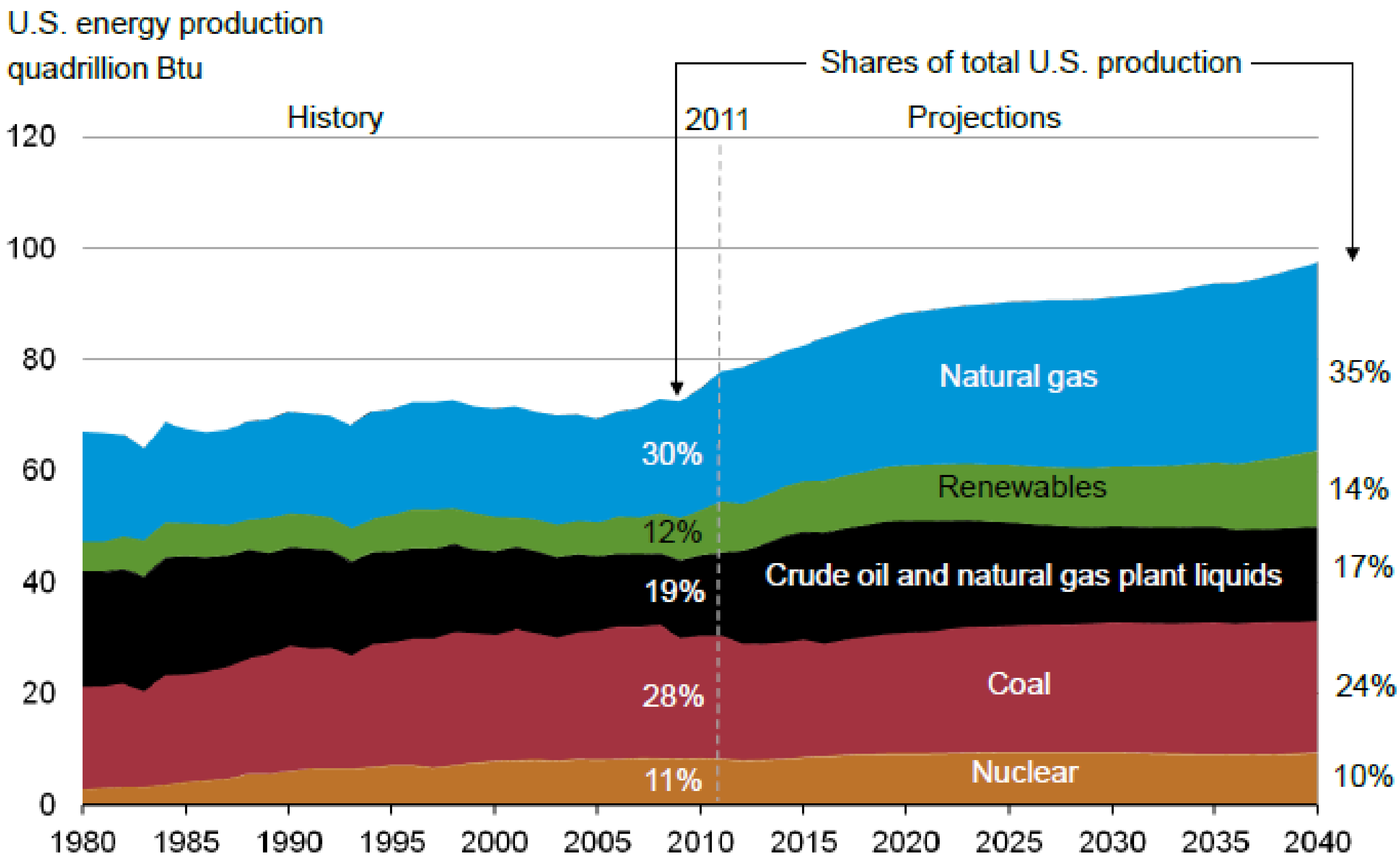
# *U.S. Energy Production and Consumption Trends*

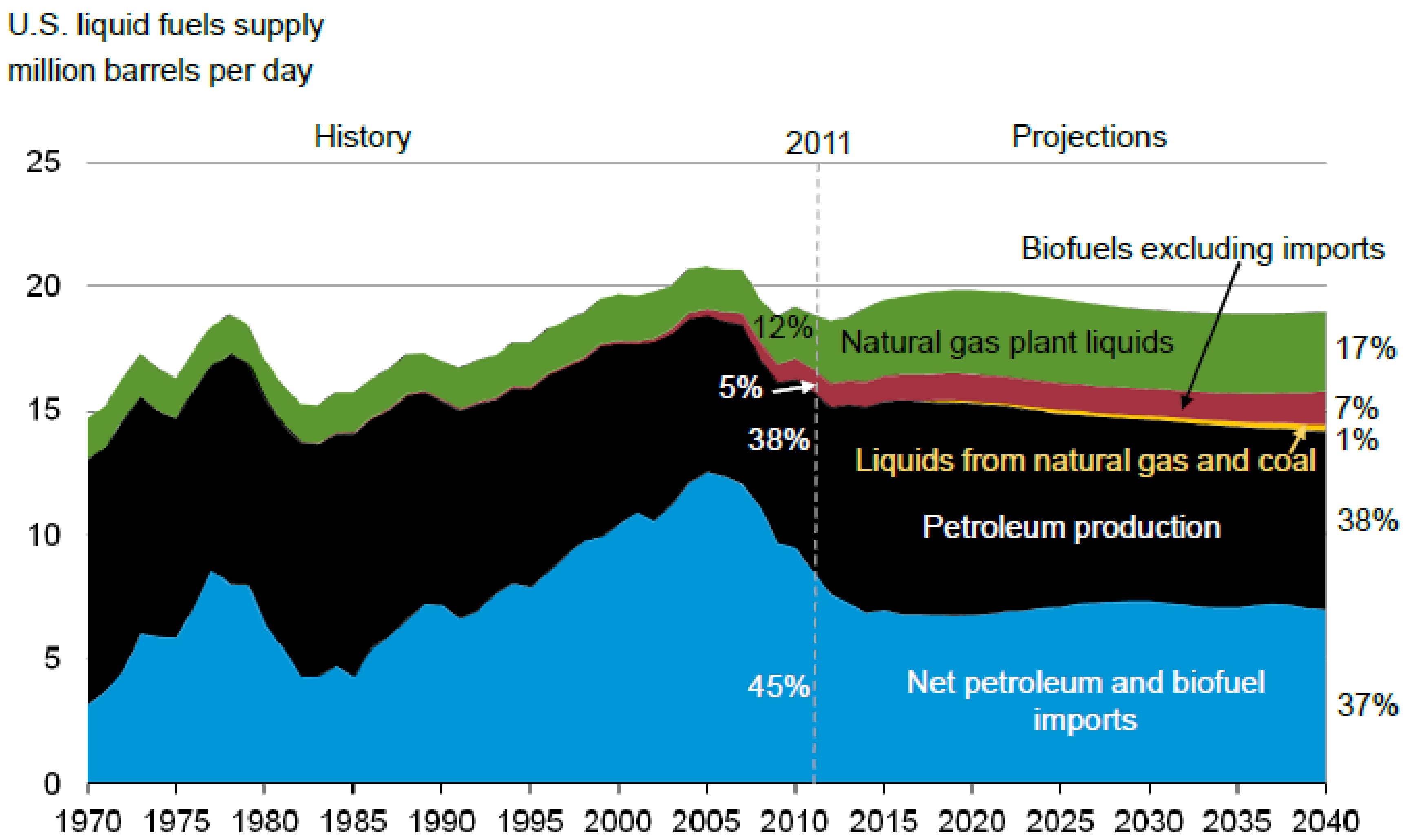
- U.S. domestic oil and natural gas production continues to grow
  - Shale gas production accounts for ¼ of total natural gas production
  - Shale oil production in North Dakota makes the state No. 2 oil producing state
- U.S. continues the uptrend in exporting natural gas and coal
- Production of ethanol reached 13.5 billion gallons in 2012; its use faces the E10 blending wall

# U.S. Production of Natural Gas, Renewables, and Liquids Will Continue to Grow



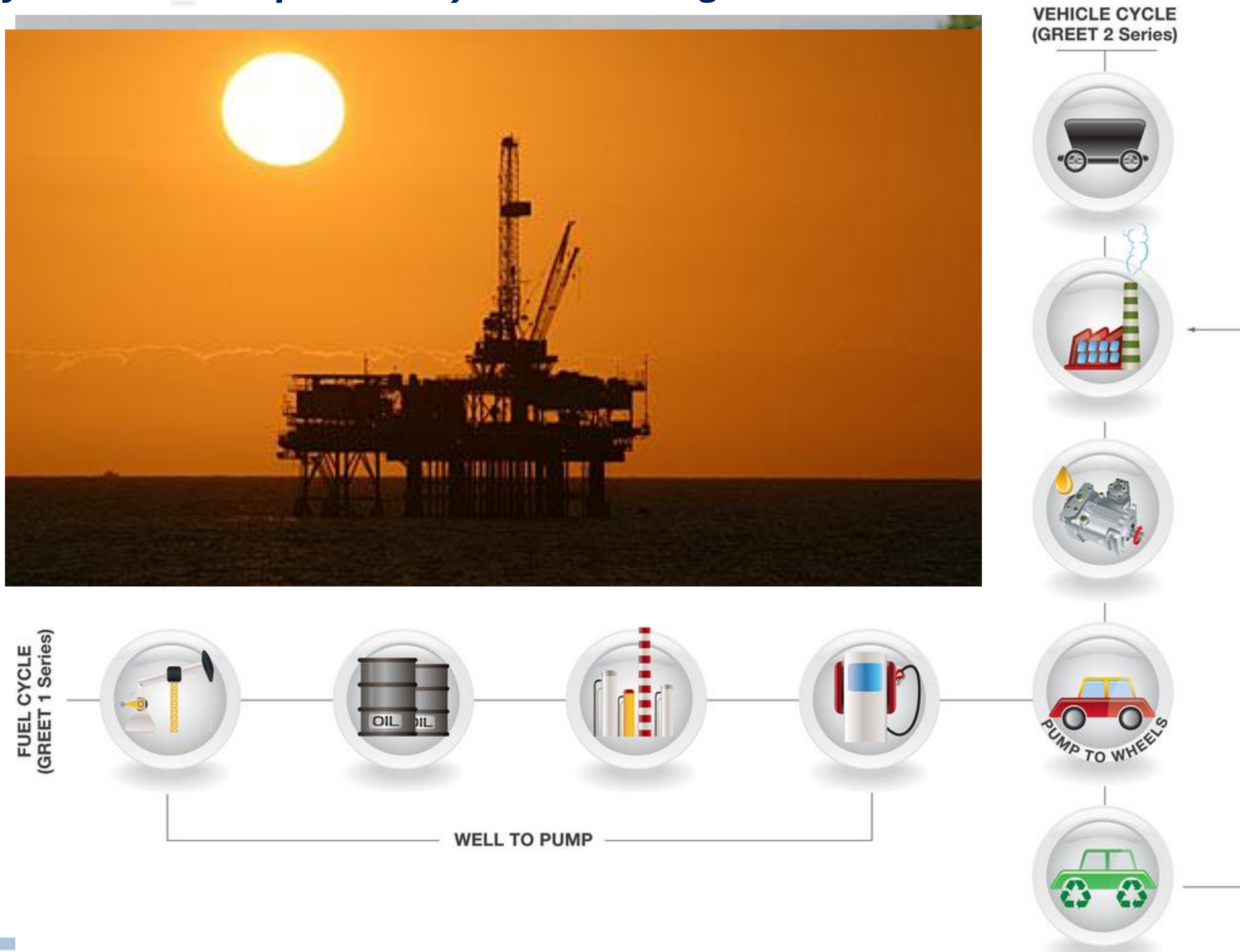

*Source: EIA, Annual Energy Outlook 2013 Early Release*

# U.S. Liquid Fuel Supply

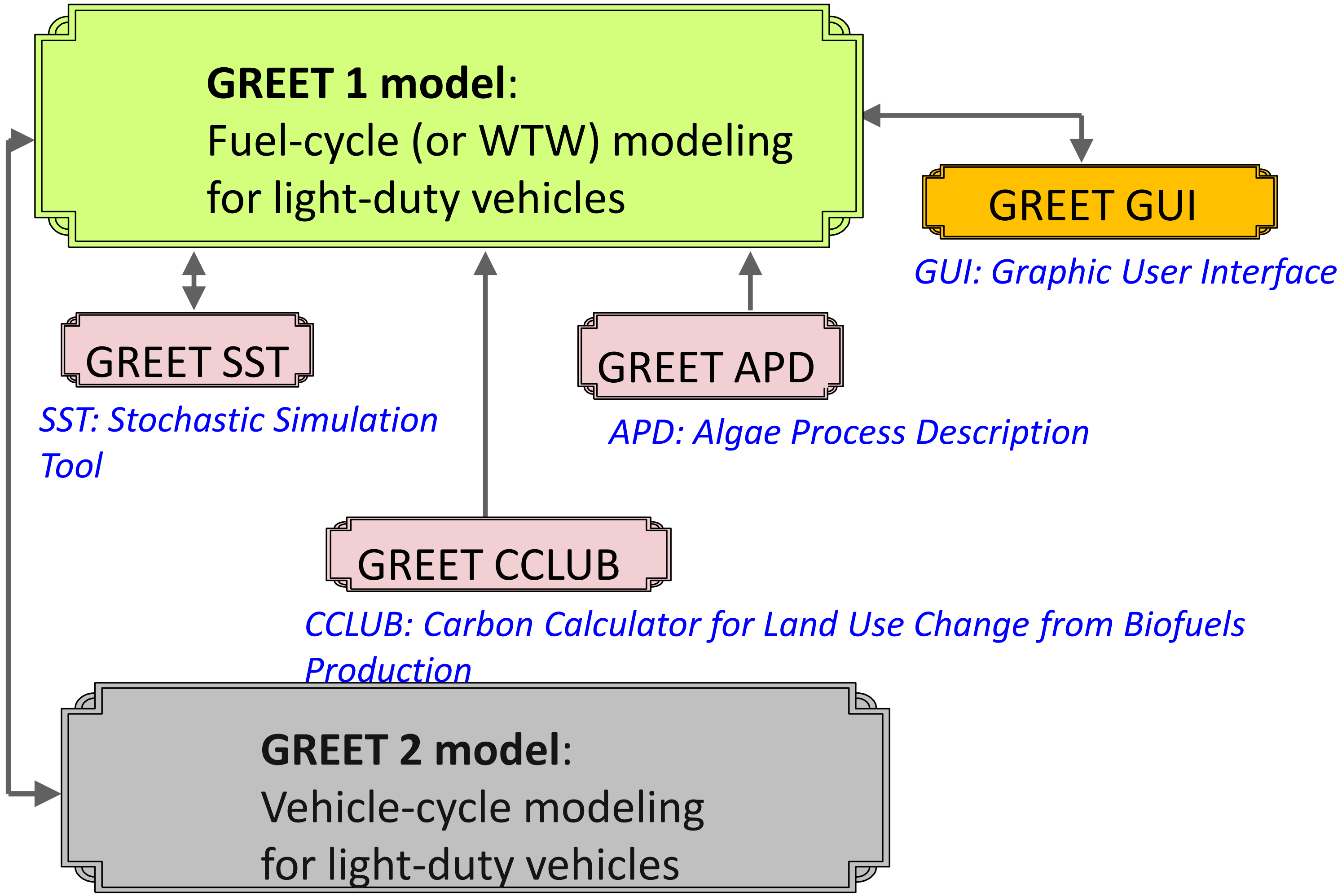



*Source: EIA, Annual Energy Outlook 2013 Early Release*

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



# The Suite of GREET Models in MS Excel



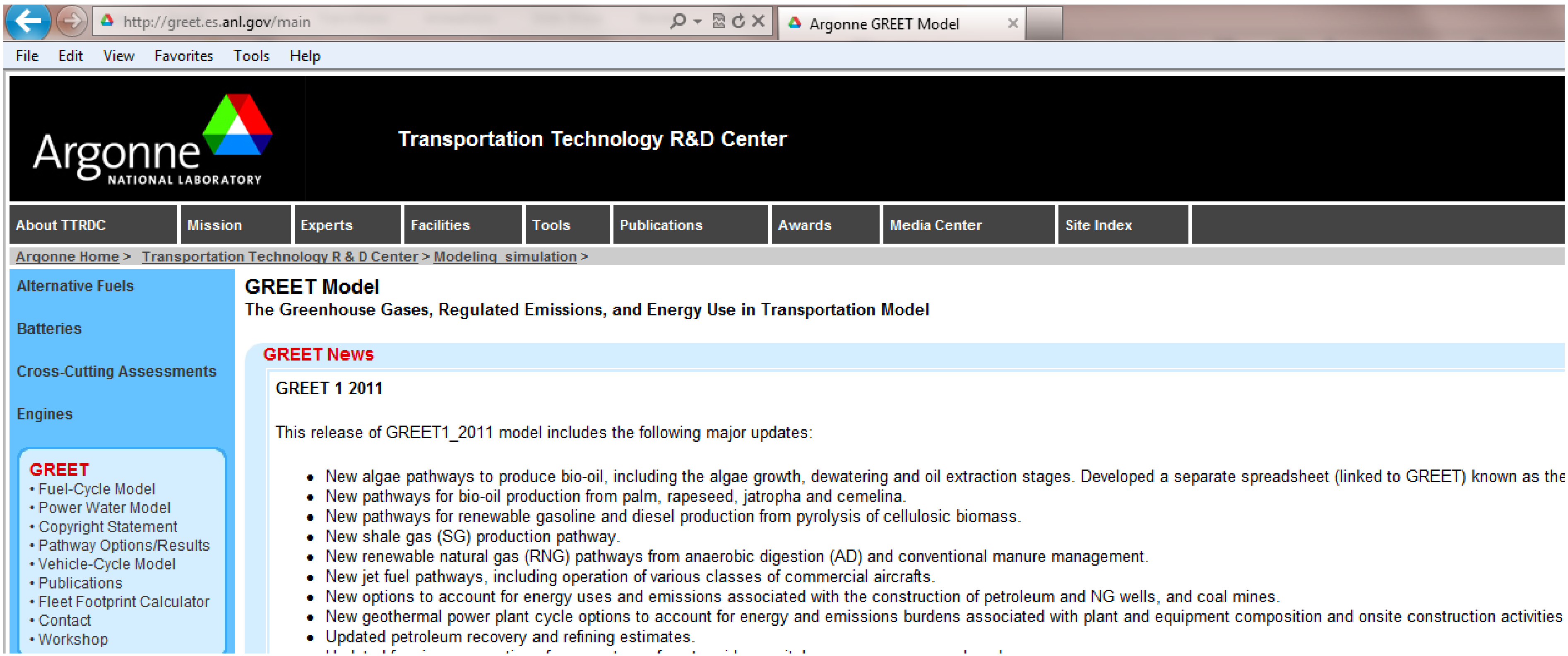
# ARGONNE'S GREET.net beta

## TAKING LIFE CYCLE ANALYSIS TO THE NEXT LEVEL

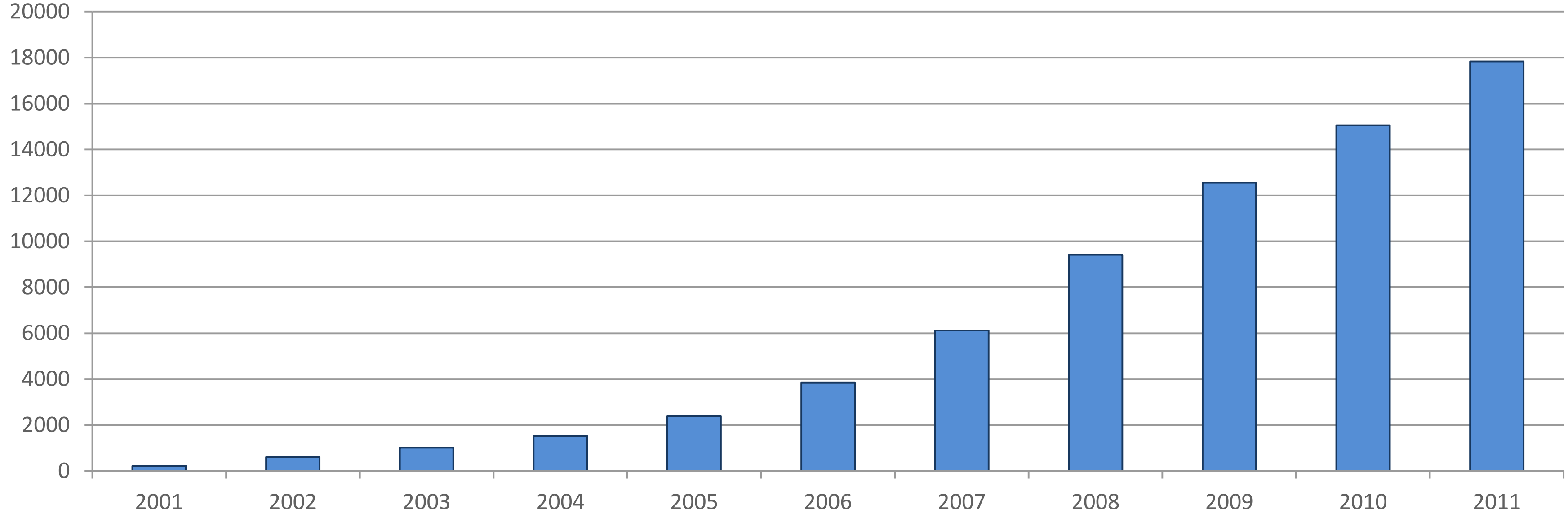
- **Build complex pathways within minutes**
  Drag and drop predefined processes to assemble a pathway
- **Add your own data**
  Create new resources, processes, technologies using simple graphical editors
- **Navigate through the model**
  Use the well to pump explorer to reveal the details of each pathway
- **Analyze results**
  Examine detailled results at different levels within the pathway
- **Share your project**
  Save all your data into an easy to share data file
- **Adaptable unit system**
  Enables users to change the representation of any result or data using their prefered units
- **Free and maintained**
  Tools and data are provided at no charge and can be updated automatically

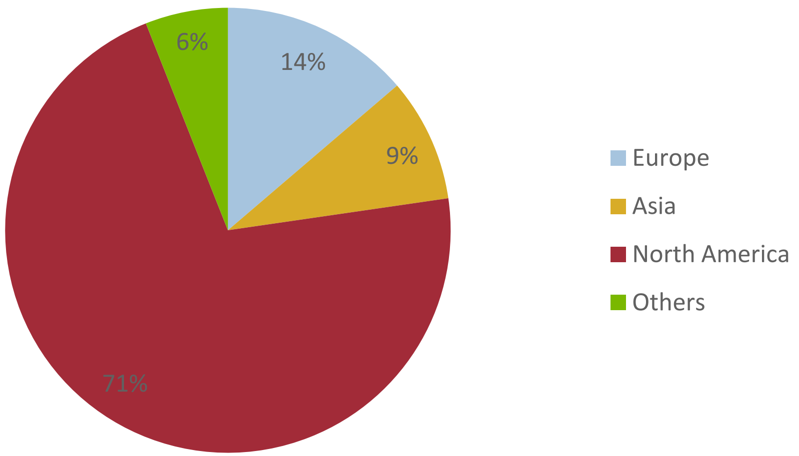
# GREET and Its Documents Are Available at Argonne's GREET Website (http://greet.es.anl.gov/)

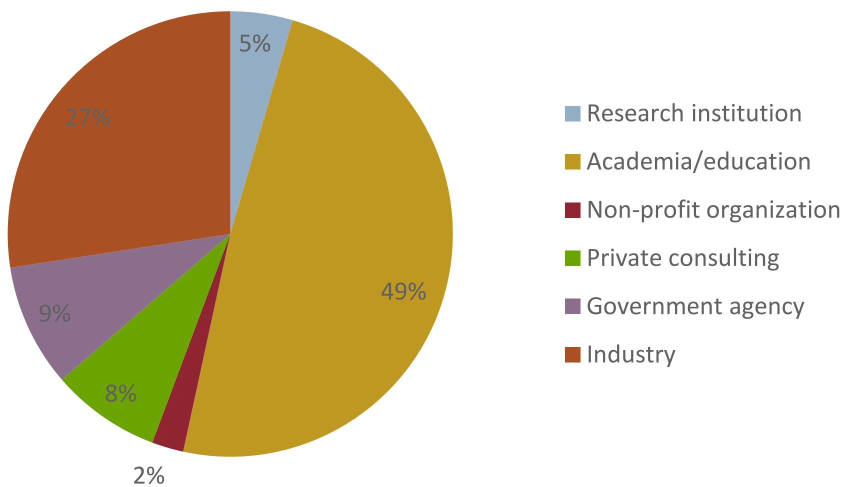
- DOE EERE has been sponsoring GREET development and applications since 1995
- The current GREET version (GREET1_2011) was released in Oct. 2011
- A new release (GREET1_2012 and GREET2_2012) is under final preparation



# There Are More Than 18,000 Registered GREET Users Worldwide



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

| | |
|---|---|
| **Petroleum**<br>Conventional<br>Oil Sands | Gasoline<br>Diesel<br>Liquefied Petroleum Gas<br>Residual Oil (to electricity)<br>Jet Fuel |
| **Natural Gas**<br>North American<br>Shale Gas<br>Non-North American | Compressed Natural Gas<br>Liquefied Natural Gas<br>Liquefied Petroleum Gas<br>Hydrogen<br>Methanol<br>Dimethyl Ether<br>Fischer-Tropsch Diesel<br>Fischer-Tropsch Jet Fuel |
| Corn | Ethanol<br>Butanol |
| Sugarcane | Ethanol |
| Soybeans | Biodiesel<br>Renewable Diesel<br>Renewable Gasoline<br>Renewable Jet Fuel |
| Coke Oven Gas<br>Petroleum Coke<br>Nuclear Energy | Hydrogen |
| Coal | Hydrogen<br>Methanol<br>Dimethyl Ether<br>Fischer-Tropsch Diesel<br>Fischer-Tropsch Jet Fuel |
| **Renewable Natural Gas**<br>Landfill Gas<br>Biogas from anaerobic digestion | Compressed Natural Gas<br>Liquefied Natural Gas<br>Hydrogen<br>Methanol<br>Dimethyl Ether<br>Fischer-Tropsch Diesel<br>Fischer-Tropsch Jet Fuel |
| **Cellulosic Biomass**<br>Switchgrass<br>Miscanthus<br>Fast Growing Trees<br>Crop Residues<br>Forest Residues | Ethanol<br>Hydrogen<br>Methanol<br>Dimethyl Ether<br>Gasoline, Diesel<br>Fischer-Tropsch Diesel<br>Fischer-Tropsch Jet Fuel |
| Residual Oil<br>Coal<br>Natural Gas<br>Biomass<br>Other Renewables (hydro, wind, solar, geothermal) | Electricity |
| Algae | Biodiesel<br>Renewable Diesel<br>Renewable Gasoline<br>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
    - Switchgrass, miscanthus, sorghum
    - Forest residues
    - Willow and poplar

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

- Cellulosic biomass via pyrolysis to
  - Renewable gasoline
  - Renewable diesel
  - Renewable jet fuel

- Renewable natural gas from
  - Landfill gas
  - Anaerobic digestion of animal wastes and other feedstocks

- Corn to butanol

- Soybeans and other oil seeds to
  - Biodiesel
  - Renewable diesel
  - Renewable gasoline
  - Renewable jet fuel

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

# *Electricity Generation Systems in GREET*

- **Coal: Steam Boiler and IGCC**
  - Coal mining and cleaning
  - Coal transportation
  - Power generation

- **Natural Gas: Steam Boiler, Gas Turbine, and NGCC**
  - NG recovery and processing
  - NG transmission
  - Power generation

- **Biomass: Steam Boiler**
  - Biomass farming and harvesting
  - Biomass transportation
  - Power generation

- **Nuclear: Light Water Reactor**
  - Uranium mining
  - Yellowcake conversion
  - Enrichment
  - Fuel rod fabrication
  - Power generation

- **Hydro Power**

- **Wind Power**

- **Residual Oil: Steam Boiler**
  - Oil recovery and transportation
  - Oil refining
  - Residual oil transportation
  - Power generation

- **Solar Power via Photovoltaics**

- **Geothermal Power**

# GREET Examines More Than 80 Vehicle/Fuel Systems

**Conventional Spark-Ignition Engine Vehicles**
- Gasoline
- Compressed natural gas, liquefied natural gas, and liquefied petroleum gas
- Gaseous and liquid hydrogen
- Methanol and ethanol

**Spark-Ignition, Direct-Injection Engine Vehicles**
- Gasoline
- Methanol and ethanol

**Compression-Ignition, Direct-Injection Engine Vehicles**
- Diesel
- Fischer-Tropsch diesel
- Dimethyl ether
- Biodiesel

**Fuel Cell Vehicles**
- On-board hydrogen storage
  - Gaseous and liquid hydrogen from various sources
- On-board hydrocarbon reforming to hydrogen

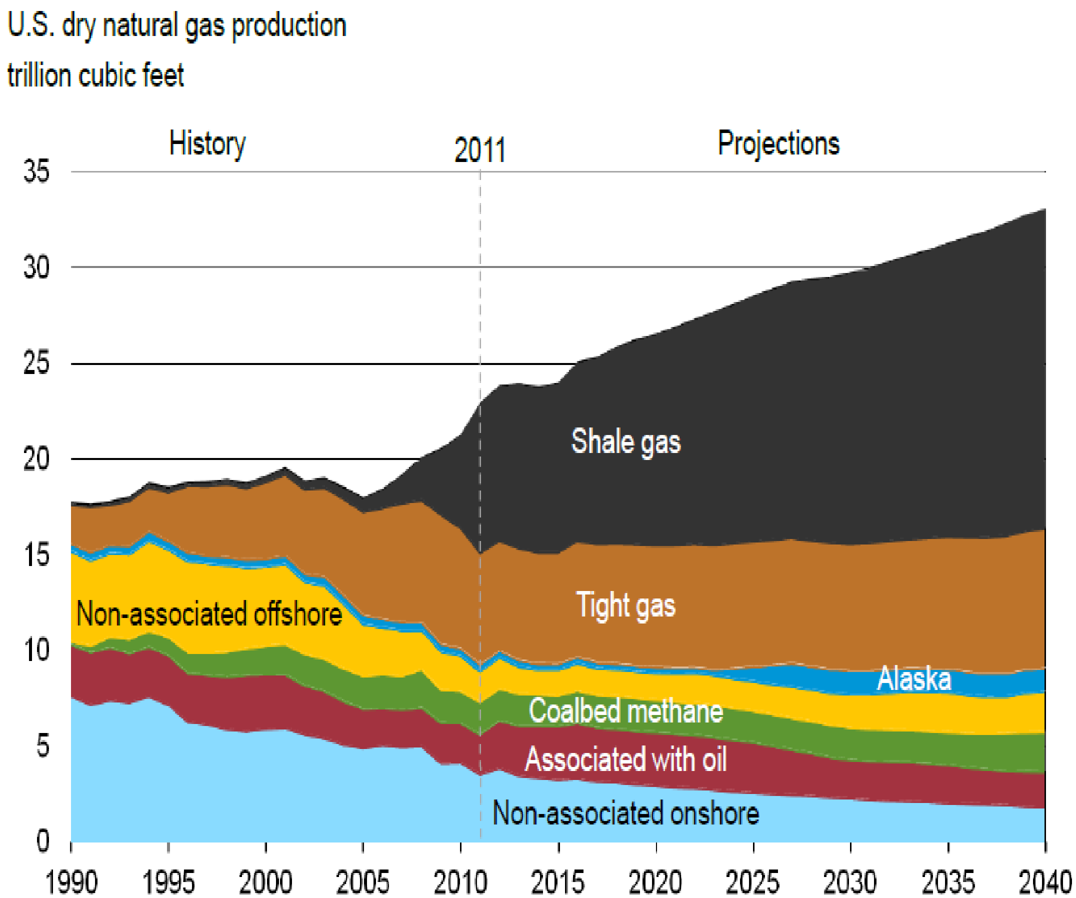
**Battery-Powered Electric Vehicles**
- Various electricity generation sources

**Hybrid Electric Vehicles (HEVs)**
- Spark-ignition engines:
  - Gasoline
  - Compressed natural gas, liquefied natural gas, and liquefied petroleum gas
  - Gaseous and liquid hydrogen
  - Methanol and ethanol
- Compression-ignition engines
  - Diesel
  - Fischer-Tropsch diesel
  - Dimethyl ether
  - Biodiesel

**Plug-in Hybrid Electric Vehicles (PHEVs)**
- Spark-ignition engines:
  - Gasoline
  - Compressed natural gas, liquefied natural gas, and liquefied petroleum gas
  - Gaseous and liquid hydrogen
  - Methanol and ethanol
- Compression-ignition engines
  - Diesel
  - Fischer-Tropsch diesel
  - Dimethyl ether
  - Biodiesel

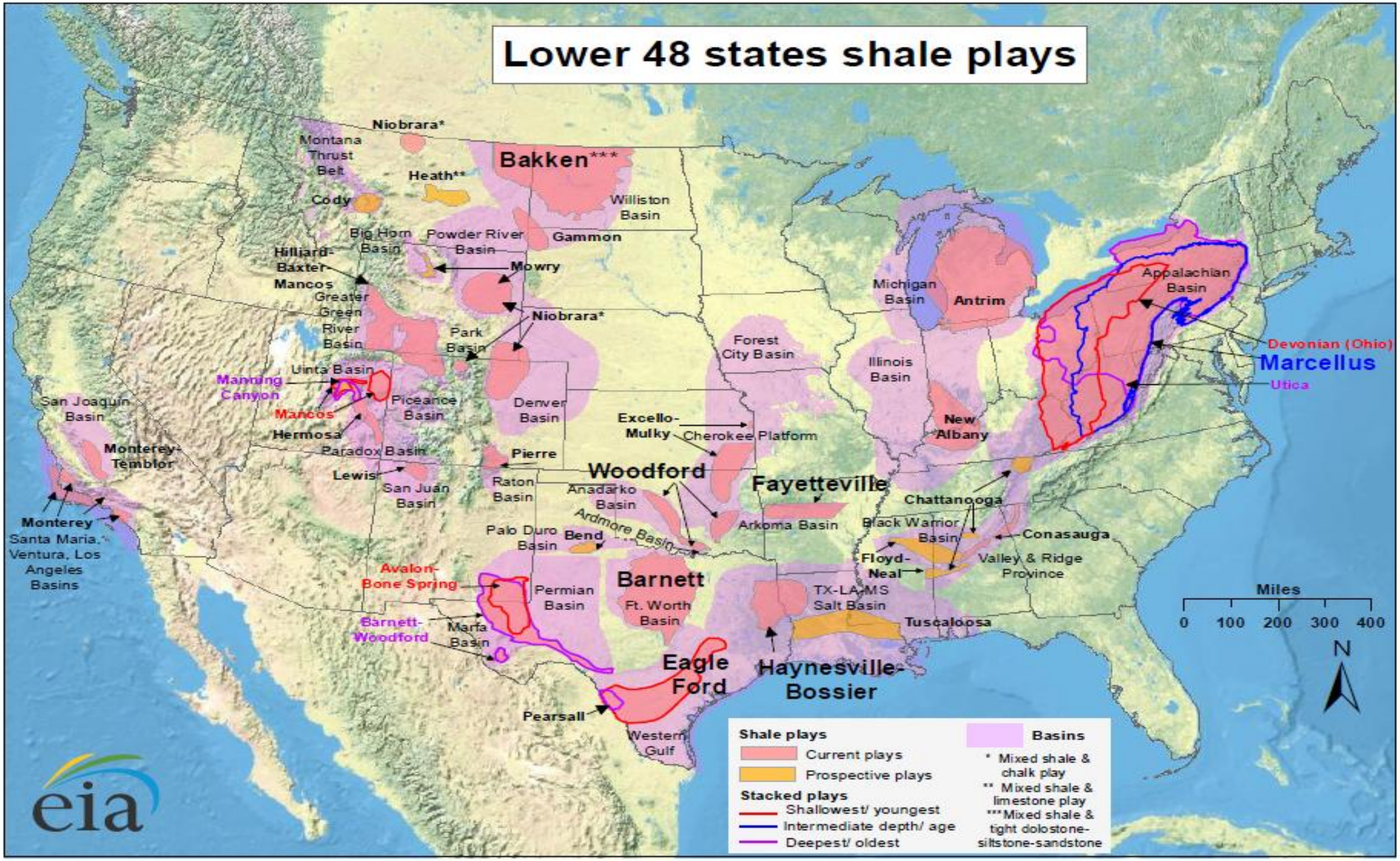
# U.S. Shale Production Will Continue to Increase Significantly

- Large-scale production made possible by advancements
  - Horizontal drilling
  - Hydraulic fracturing
- Has generated interest in expanding NG use in several sectors
  - Expansion into vehicles would displace petroleum
  - But what are the GHG implications?

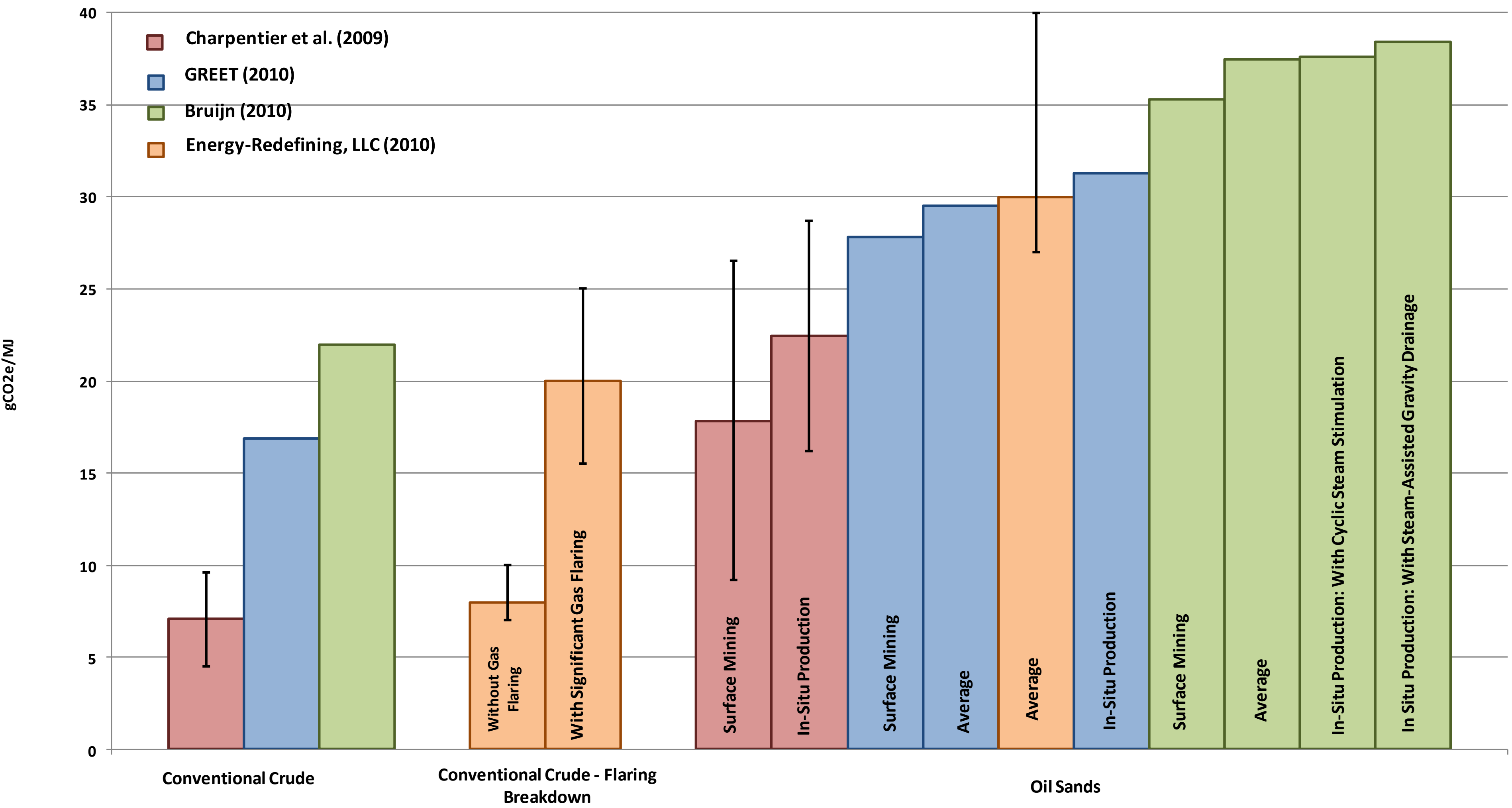



*Source: EIA, Annual Energy Outlook 2013 Early Release*

# U.S. Shale Oil and Shale Gas Plays; Domestic Oil Transportation Logistics Challenges



# Well-to-Pump GHG Emissions of Petroleum Gasoline

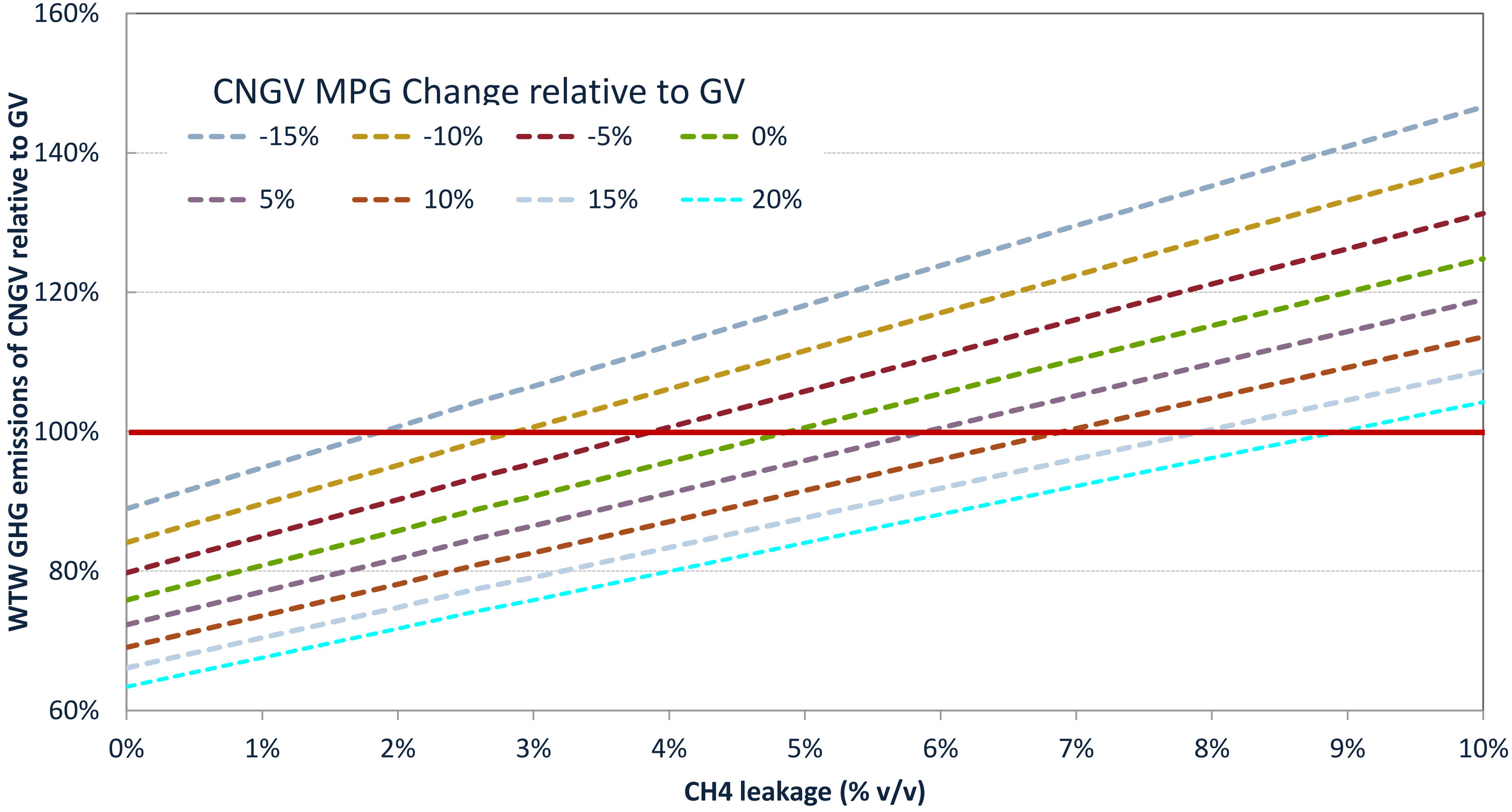



Gasoline combustion: about 75 g/MJ GHG emissions

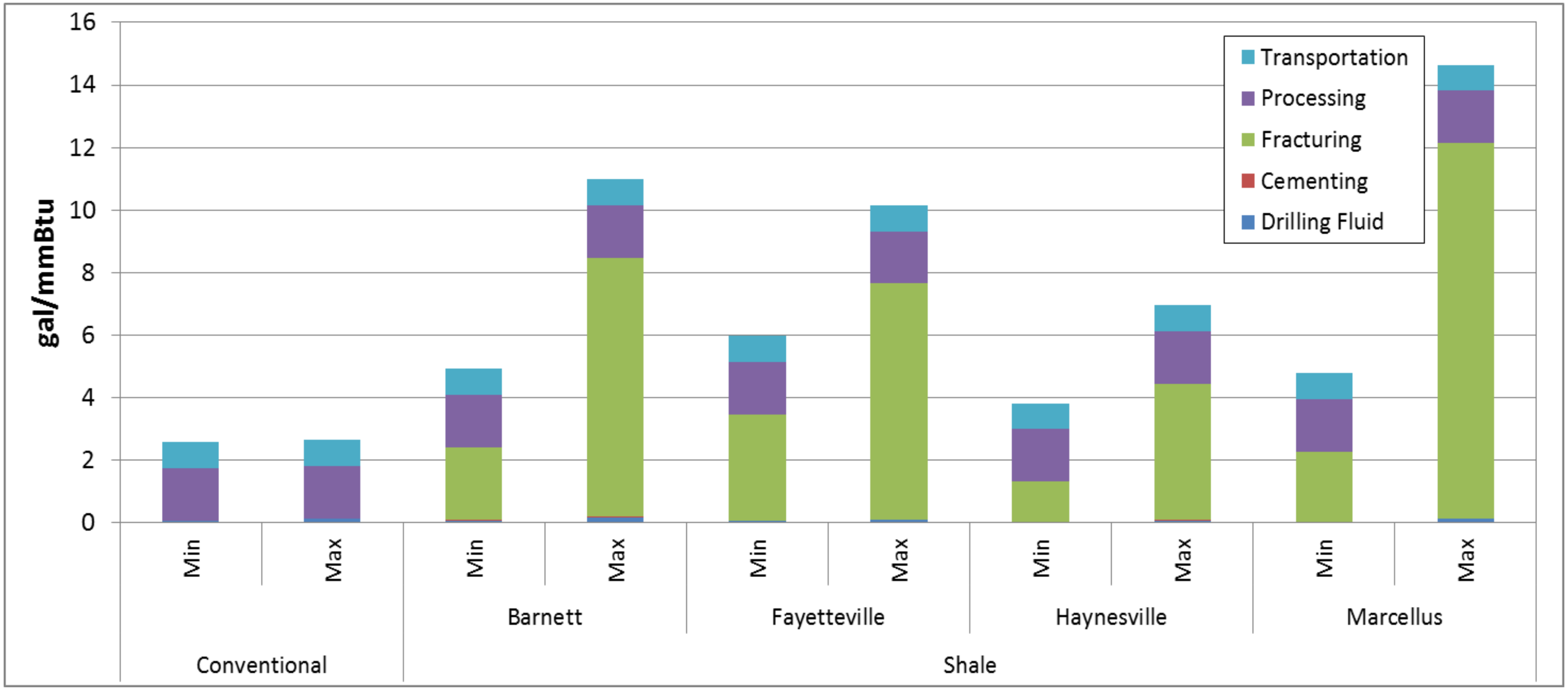
# Methane Leakage of Natural Gas Production and Distribution Is A Major Concern

| Sector | $CH_4$ Emissions: Percent of Volumetric NG Produced | | | | | | |
|---|---|---|---|---|---|---|---|
| | EPA - Inventory (2011) | GREET Conv. Gas (2012) | GREET Shale Gas (2012) | NOAA - DJ Basin (2012) | NREL - Barnett Shale (2012) | API Survey (2012) | EPA - Inventory (2013) |
| Gas Field | 1.18 | 1.93 (0.62 - 4.19) | 1.19 (0.36 - 3.95) | 2.3 - 7.7 | 0.9 | 0.52 | 0.44 |
| Completion/ Workover | | 0.003 (0.002 - 0.005) | 0.46 (0.006 - 2.75) | | 0.7 | | |
| Unloading | | 1.20 (0.27 - 2.98) | 0 | | 0 | | |
| Other Sources | | 0.73 (0.35-1.20) | 0.73 (0.35-1.20) | | 0.2 | | |
| Processing | 0.16 | 0.15 (0.06 - 0.23) | 0.15 (0.06 - 0.23) | | 0 | | 0.16 |
| Transmission | 0.38 | 0.39 (0.20 - 0.58) | 0.39 (0.20 - 0.58) | | 0.4 | | 0.36 |
| Distribution | 0.26 | 0.28 (0.09 - 0.47) | 0.28 (0.09 - 0.47) | | | | 0.23 |
| Total | 1.98 | 2.75 (0.97 - 5.47) | 2.01 (0.71 - 5.23) | | | | 1.19 |

# WTW GHG Emissions of CNG Vehicles vs. Gasoline Vehicles - Methane Leakage and CNGV Efficiency Are Two Key Factors



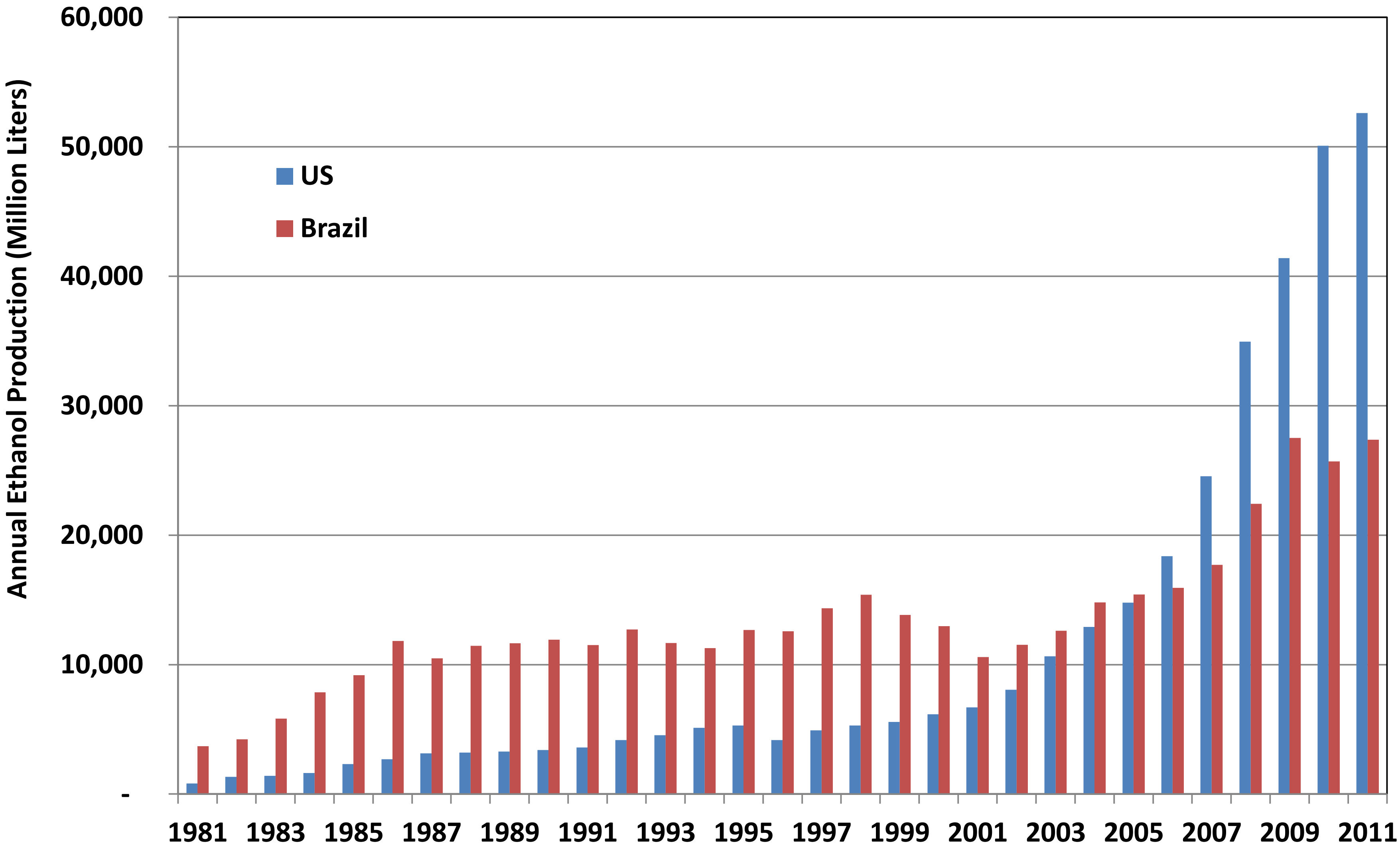
# Water Consumption of Shale Gas and Conventional Gas




Source: Clark and Horner, 2012

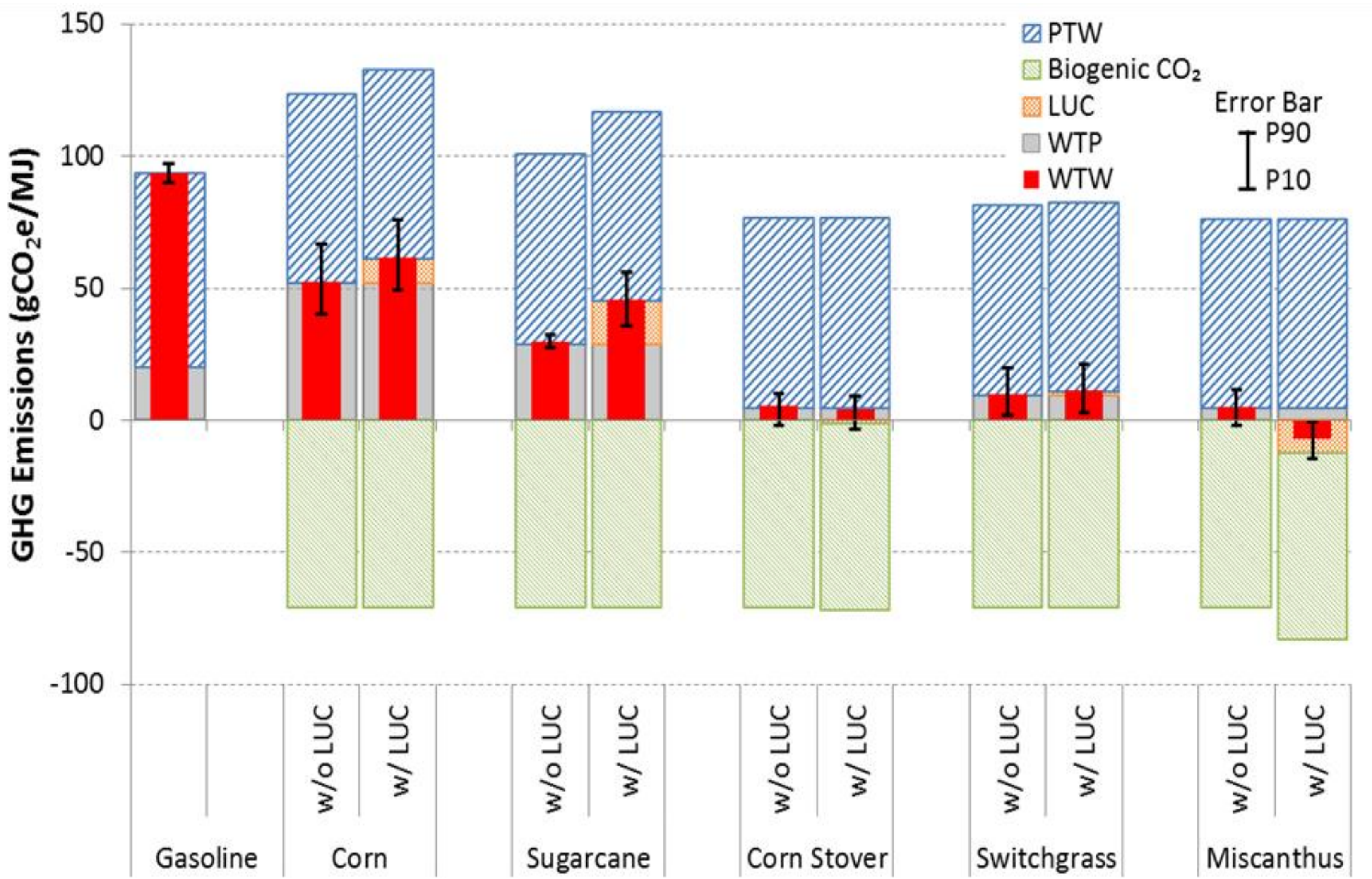
- Drilling of a shale gas well may consume 5 million gallons of water
- Water consumption varies significantly by shale play
- Recycling of flowback reduces consumption
  - 95% recycling in Marcellus
  - 20% recycling in Barnett and Fayetteville

# U.S. and Brazil and the Two Major Biofuel Producing Countries



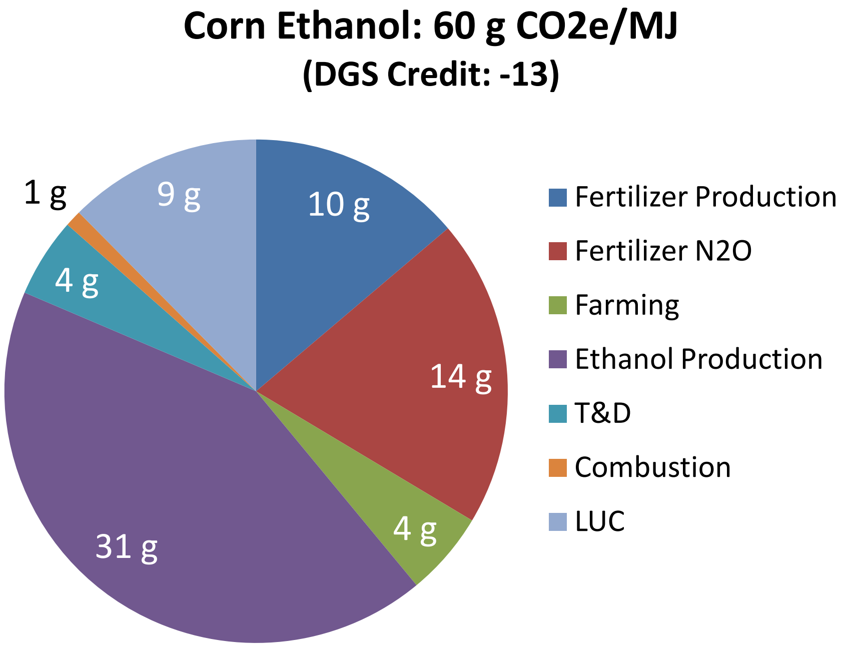

From Wang et al. (2012)

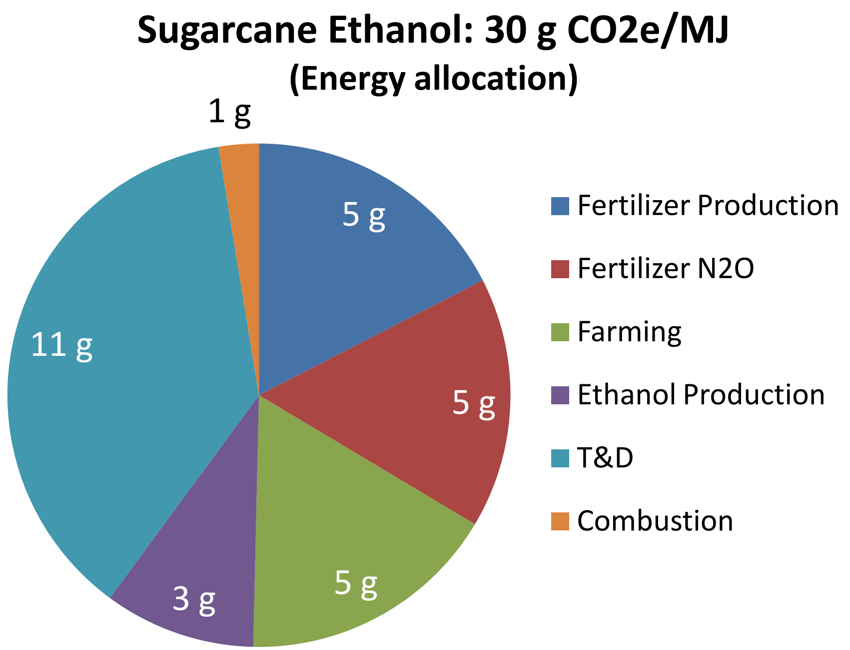
# LCA GHG Emissions of Gasoline and Bioethanol Pathways




Wang M., et al., 2012, *Environ. Research Letters*

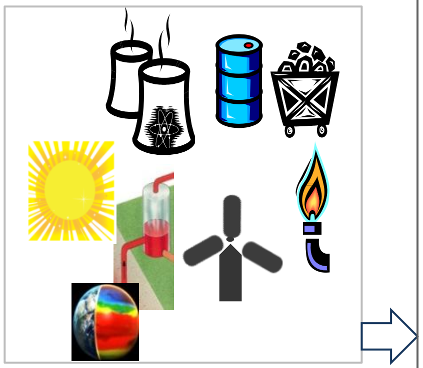
# GHG Emission Sources for Corn and Sugarcane Ethanol



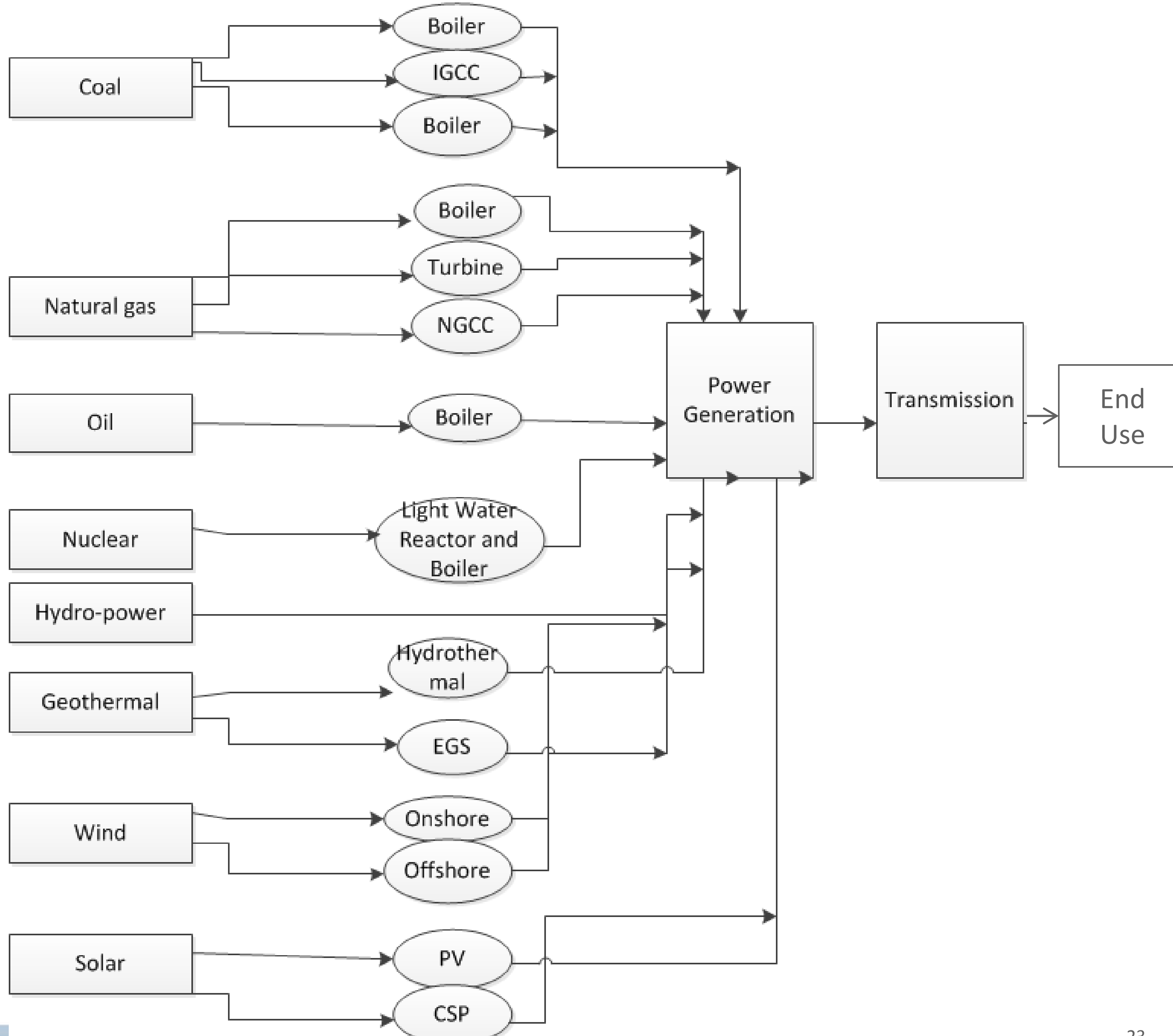

From Wang et al. (2012)

# *Life-Cycle Analysis of Electricity*

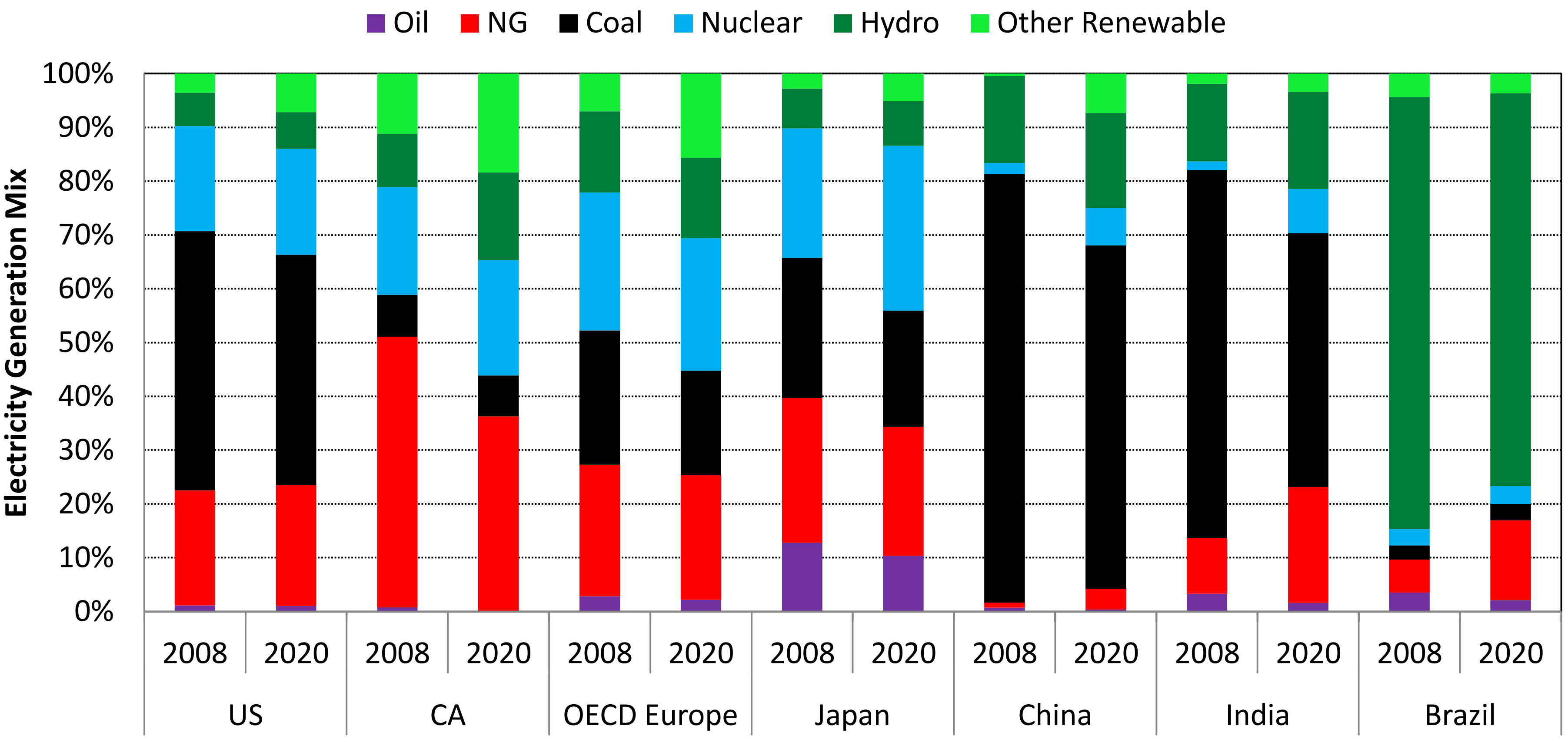


**Fuels**
(production, T&D)

**Feedstock**
(recovery, processing, T&D)

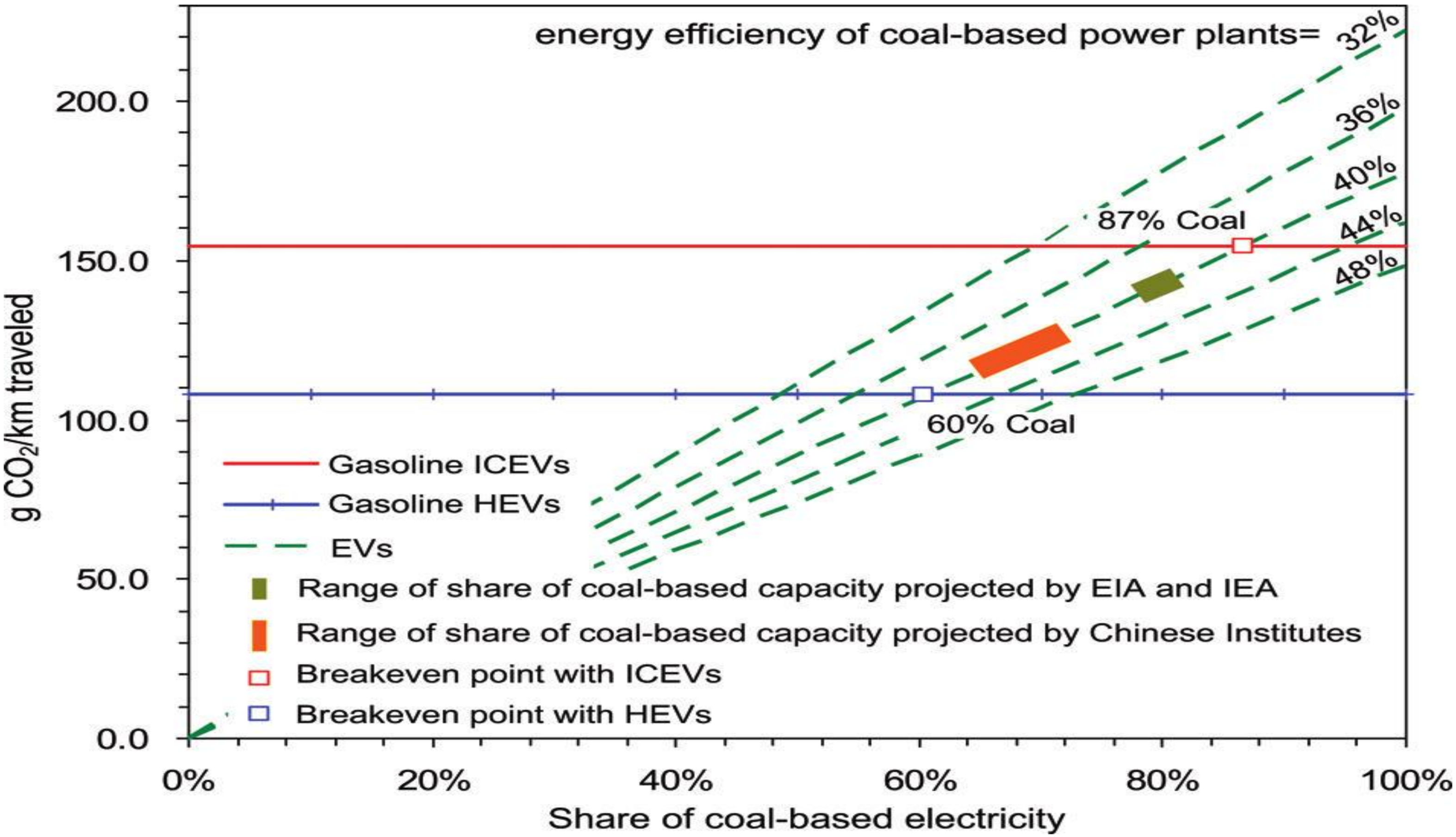


# Electricity Generation Mixes in Different Countries: Implication for Transportation Electrification



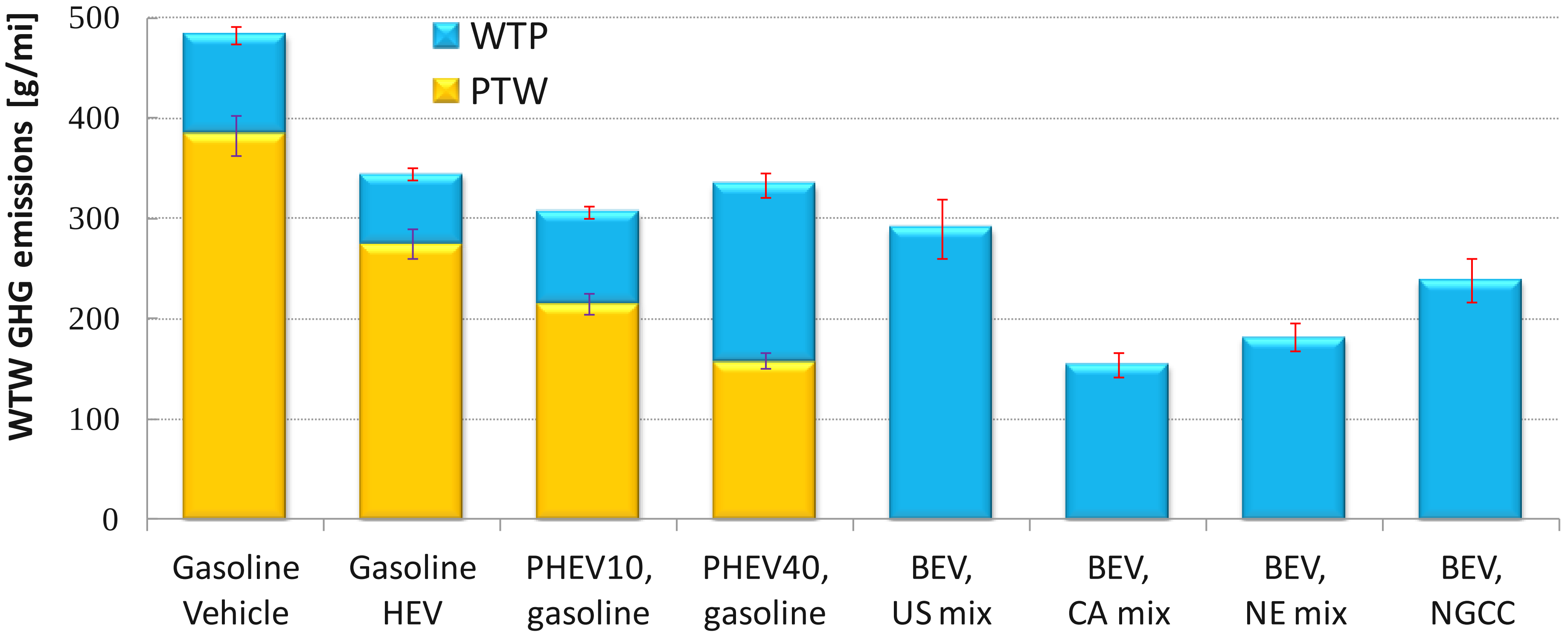

From Wang et al. (2011)

# GHG Emissions of Battery-Powered Electric Vehicles Depend Primarily on Share and Efficiency of Coal Power Plants

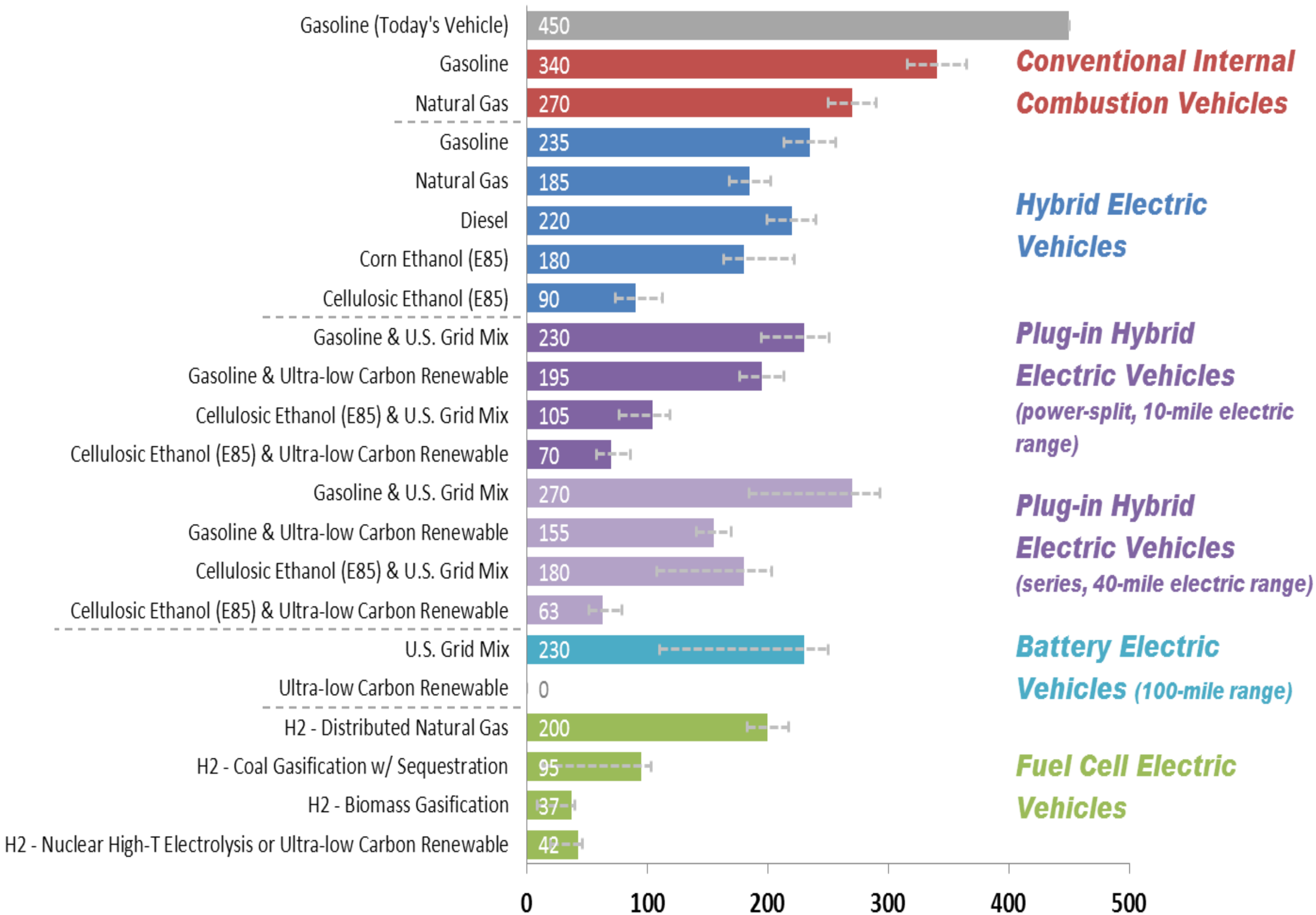



From Huo et al. (2010)

# Plug-in Vehicles Provide Varying GHG Emissions Reductions Depending on the Electric Generation Mix for Recharging



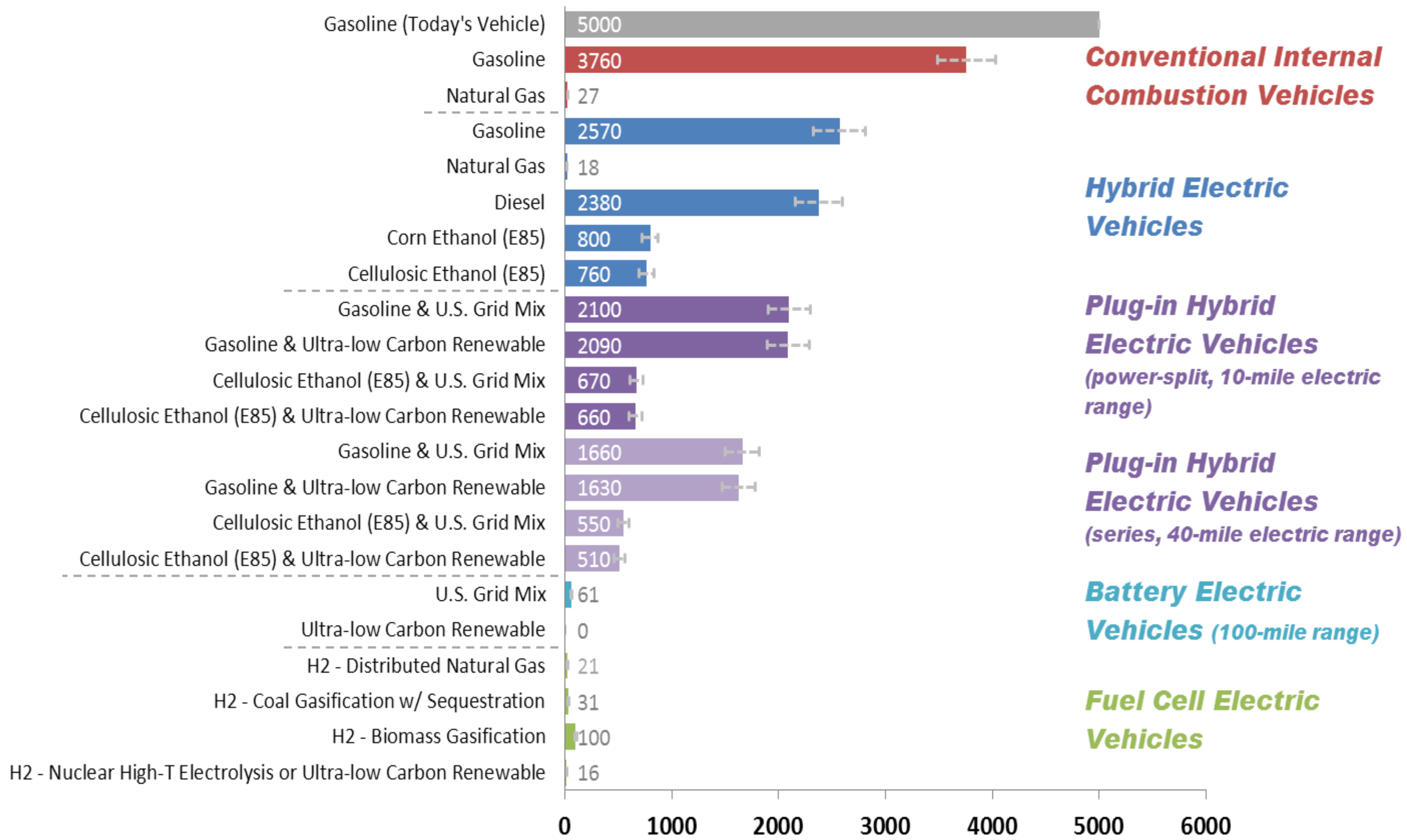
# WTW Results: GHG Emissions of a Mid-Size Car (g/mile)




*Low/high band: sensitivity to uncertainties associated with projection of fuel economy and fuel pathways*

(DOE EERE 2010, Record 10001)

# WTW Results: Petroleum Use of a Mid-Size Car (BTU/mile)




*Low/high band: sensitivity to uncertainties associated with projection of fuel economy and fuel pathways*

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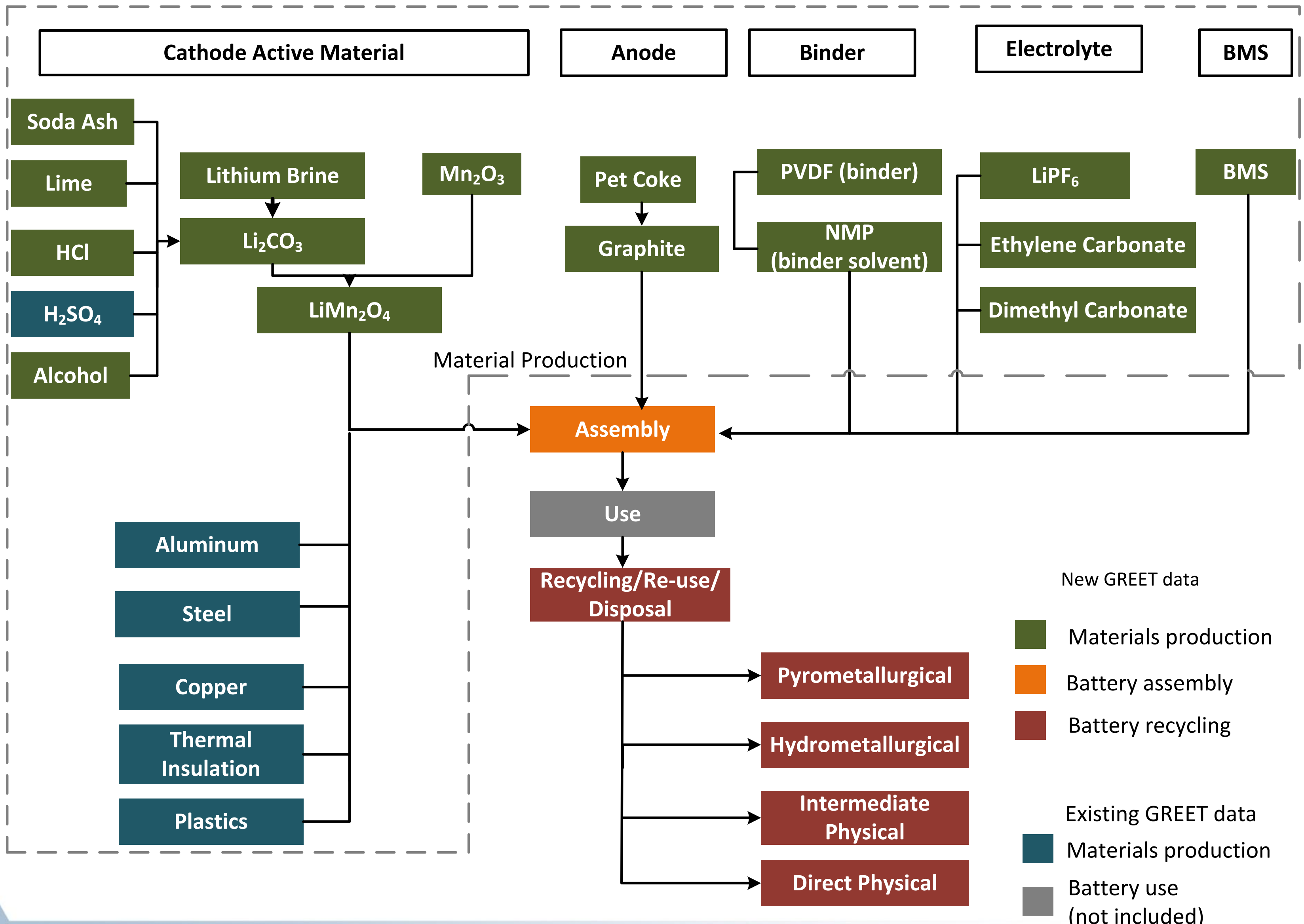
# Battery Life-Cycle Analysis Covers Battery Production and Recycling



# GREET Battery LCA Approach

- With output from the **Autonomie** model, identify power and energy specifications for batteries for use in hybrid electric vehicles, plug-in hybrid electric vehicles, and battery electric vehicles
- Develop material inventories for these three battery types with the **BatPaC** model
- Establish material and energy flows for each battery component
- Estimate the energy consumed during battery assembly and battery recycling
- Assemble all data in **GREET**
- Analyze data to address key questions

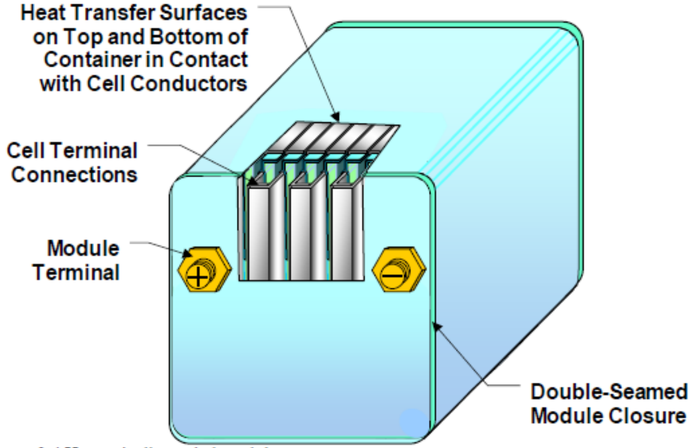
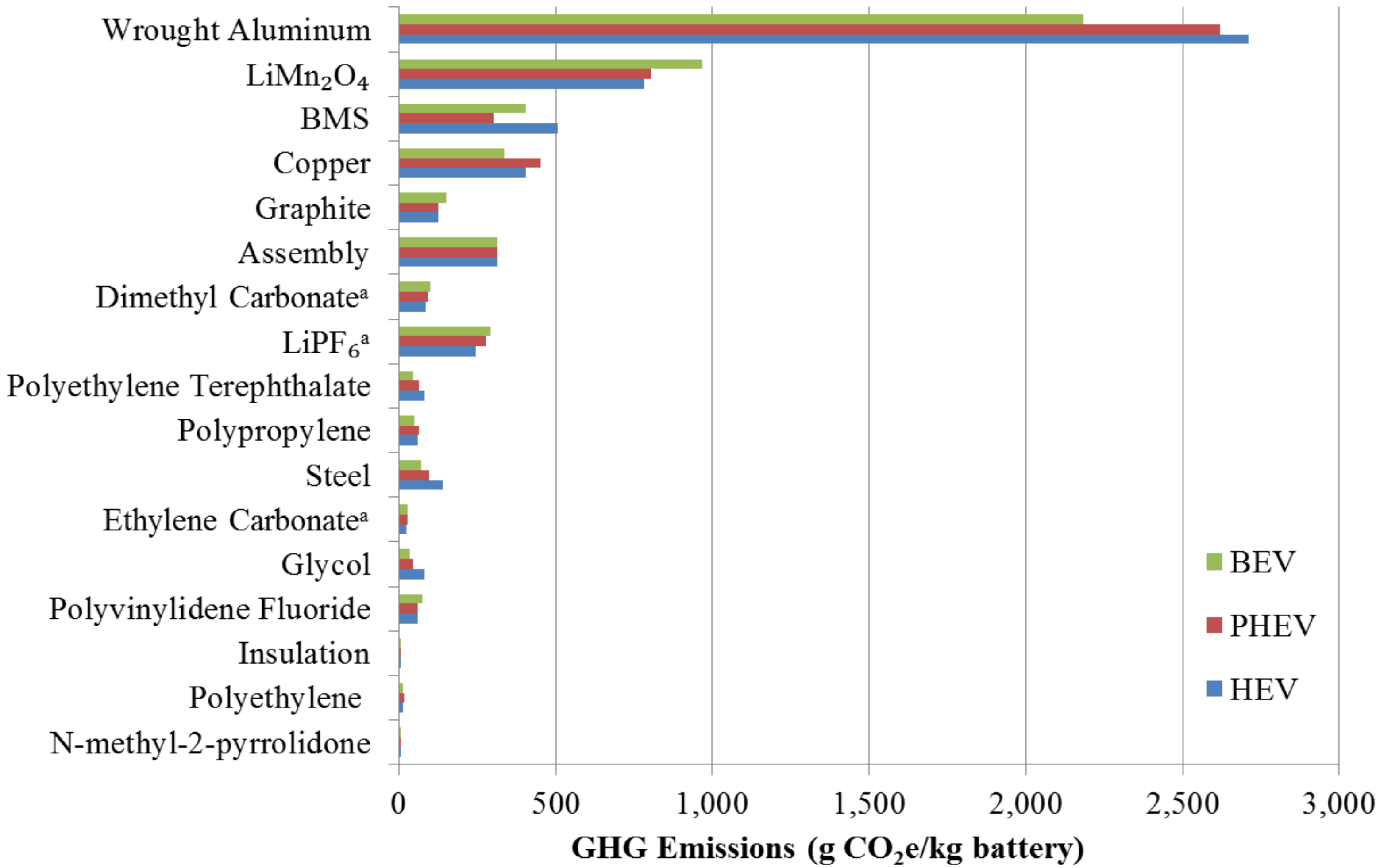



Figure 2.4 Hermetically-sealed module

# Structural and Cathode Materials Dominate Lithium-Ion Battery LCA GHG Emissions




Dunn, J.B. et al. (2012)

For GREET model and technical reports, please visit

http://greet.es.anl.gov