GREET^{TM} Life-Cycle Analysis Model

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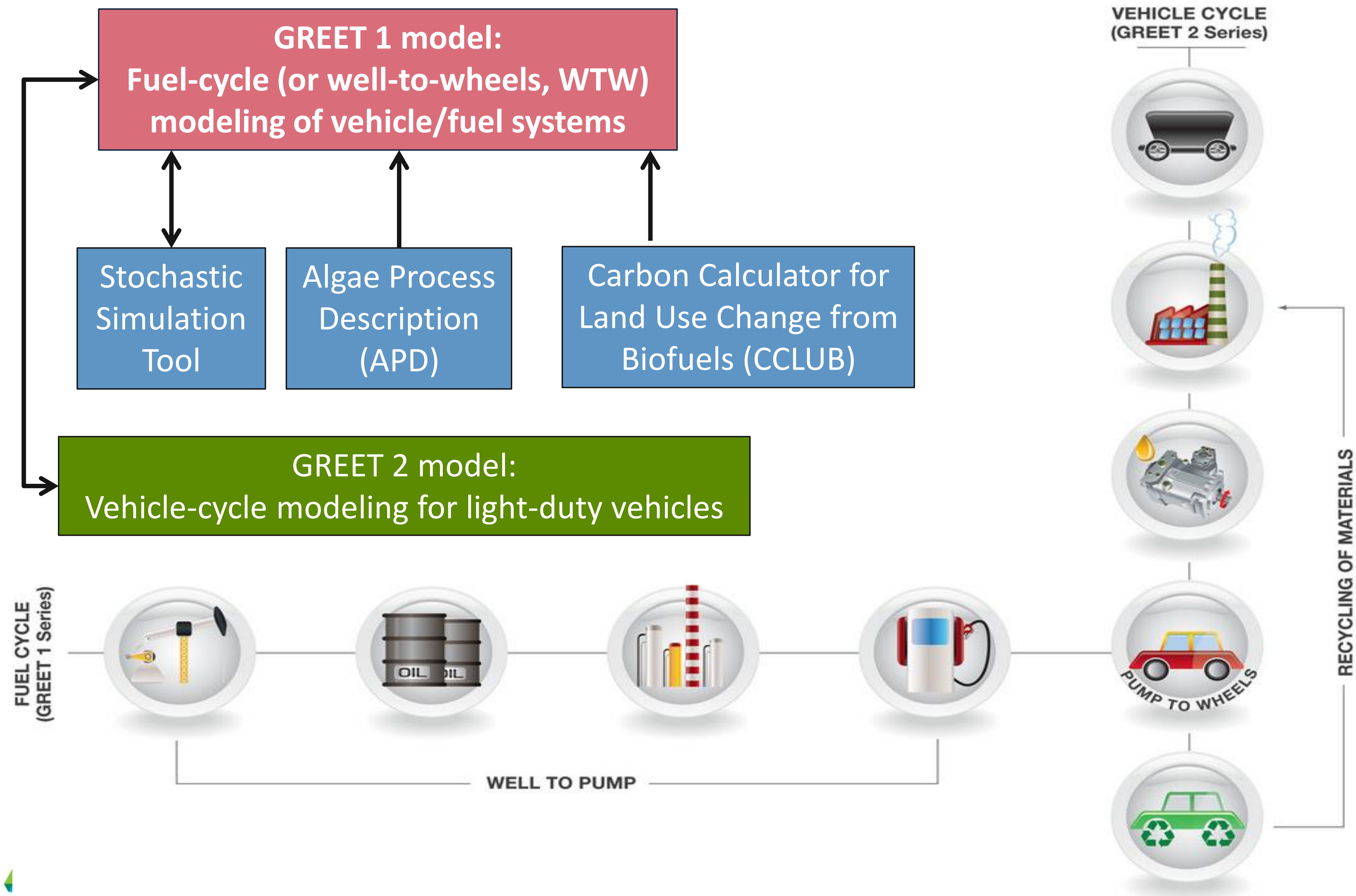
The GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) Model



GREET development has been supported by several DOE Offices since 1995

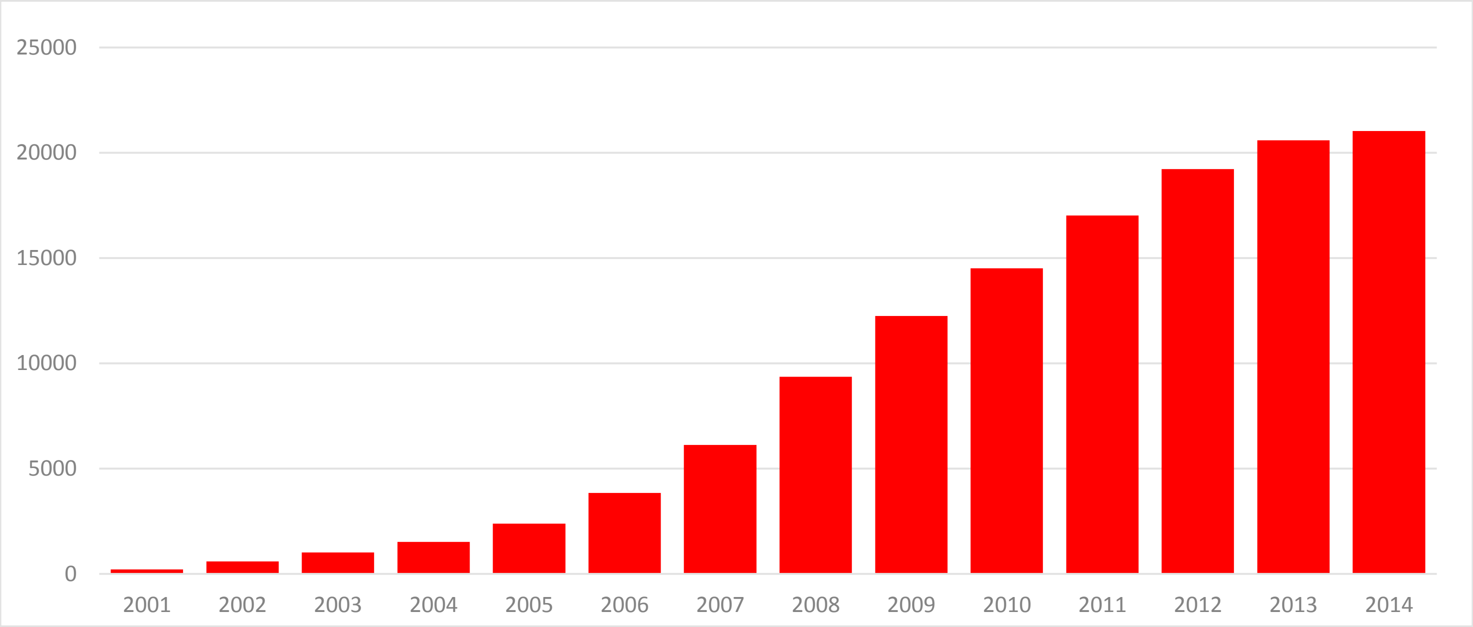
- Vehicle Technology Office (VTO)
- Fuel-Cell Technology Office (FCTO)
- Energy Policy and Systems Analysis (EPSA)
- Bioenergy Technology Office (BETO)
- Geothermal Technology Office (GTO)

GREET has been in public domain and free of charge since it inception in 1995- Updated and expanded annually

Examples of major uses of GREET

- DOE, USDA, and the Navy use GREET for R&D decisions
- US EPA used GREET for RFS and vehicle GHG standard developments
- CARB developed CA-GREET for its Low-Carbon Fuel Standard compliance
- DOD DLA-Energy uses GREET for alternative fuel purchase requirements
- Energy industry (especially new fuel companies) uses it for addressing sustainability of R&D investments
- Auto industry uses it for R&D screening of vehicle/fuel system combinations
- Universities uses GREET for education on technology sustainability of various fuels

There are more than 23,000 registered GREET users globally



- Geographically, 71% in North America, 14% in Europe, 9% in Asia
- 57% in academia and research, 33 % in industries, 8% in governments

GREET outputs include energy use, greenhouse gases, criteria pollutants and water consumption for vehicle and energy systems

- **Energy use**
  - Total energy: fossil energy and renewable energy
    - Fossil energy: petroleum, natural gas, and coal (they are estimated separately)
    - Renewable energy: biomass, nuclear energy, hydro-power, wind power, and solar energy
- **Greenhouse gases (GHGs)**
  - CO_2, CH_4, N_2O, and black carbon
  - CO_{2e} of the three (with their global warming potentials)
- **Air 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)
- **Water consumption**
- **GREET LCA functional units**
  - Per service unit (e.g., mile driven)
  - Per unit of output (e.g., million Btu, MJ, gasoline gallon equivalent)
  - Per units of resource (e.g., per ton of biomass)

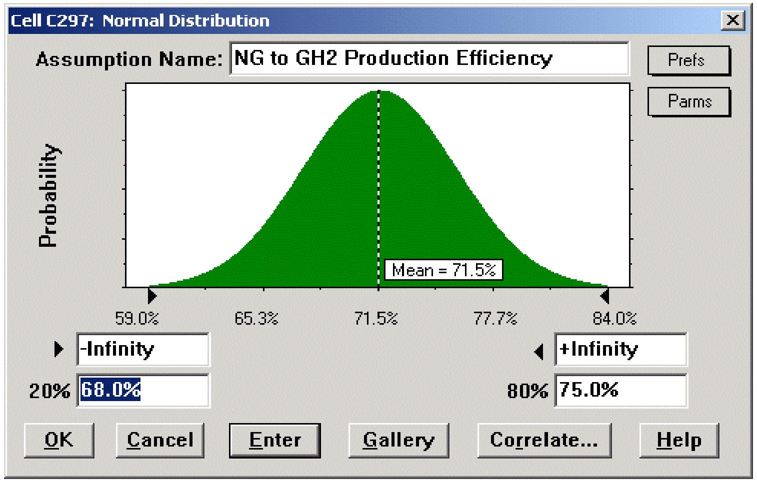
GREET includes more than 100 fuel production pathways from various energy feedstock sources

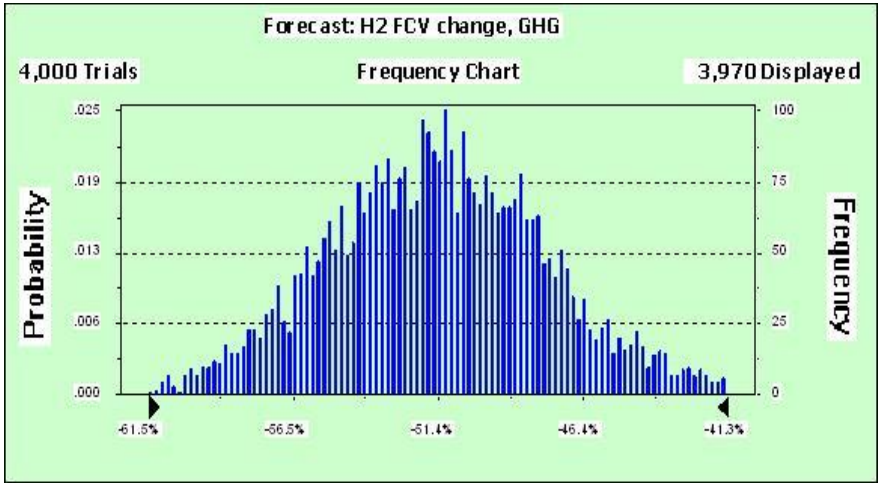
Feedstock	Fuel
Petroleum Conventional Oil Sands	**Gasoline** Diesel Jet Fuel Liquefied Petroleum Gas Naphtha Residual Oil
Coal	**Hydrogen** Fischer-Tropsch Diesel Fischer-Tropsch Jet Methanol Dimethyl Ether
Natural Gas North American Non-North American Shale gas **Renewable Natural Gas** Landfill Gas Animal Waste Waste water treatment	Compressed Natural Gas Liquefied Natural Gas Liquefied Petroleum Gas Methanol Dimethyl Ether Fischer-Tropsch Diesel Fischer-Tropsch Jet Fischer-Tropsch Naphtha **Hydrogen**
Coke Oven Gas **Petroleum Coke** **Nuclear Energy**	**Hydrogen**

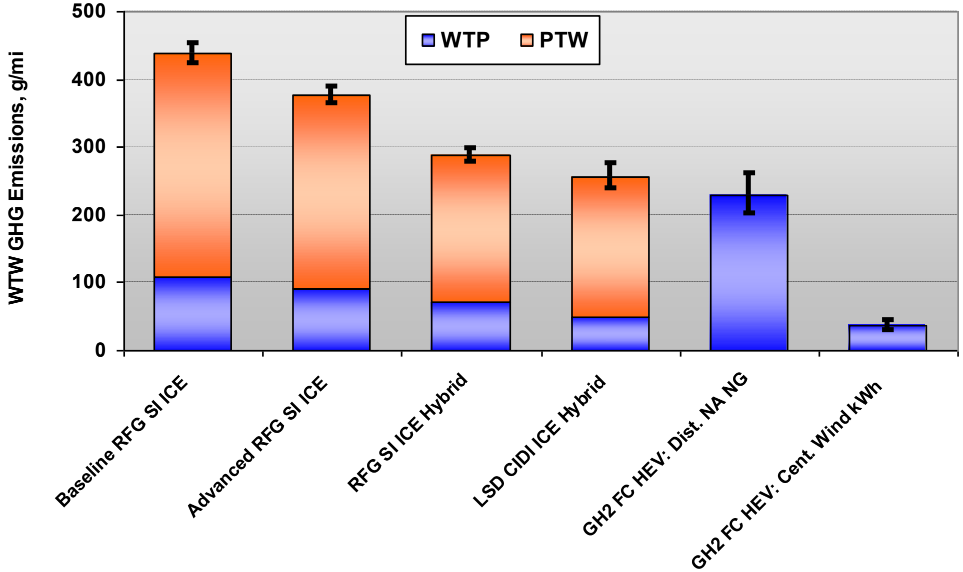
Feedstock	Fuel
Corn	Ethanol Butanol
Sugarcane	Ethanol
Soybeans Palm Rapeseed Jatropha Camelina Algae	Biodiesel Renewable Diesel Renewable Gasoline Renewable Jet
Cellulosic Biomass Switchgrass Willow/Poplar Crop Residues Forest Residues Miscanthus	Ethanol **Hydrogen** Methanol Dimethyl Ether Fischer-Tropsch Diesel Fischer-Tropsch Jet Pyro Gasoline/Diesel/Jet
Residual Oil Coal Natural Gas Biomass **Other Renewables**	**Electricity** → **Hydrogen**

GREET is designed with stochastic simulation capabilities to address variabilities and uncertainties

Distribution-Based Inputs Generate Distribution-Based Outputs







GREET Modeling Approach

- **Build LCA modeling capacity with the GREET model**
  - Build a consistent LCA platform with reliable, widely accepted methods/protocols
  - Address emerging LCA issues
  - Access to primary data sources and conduct detailed analysis
  - Document sources of data, modeling and analysis approach, and results/conclusions
  - Maintain openness and transparency of LCAs by making GREET and its documentation publicly available
  - Primarily process-based LCA approach (the so-called attributional LCA); some features of consequential LCA are incorporated

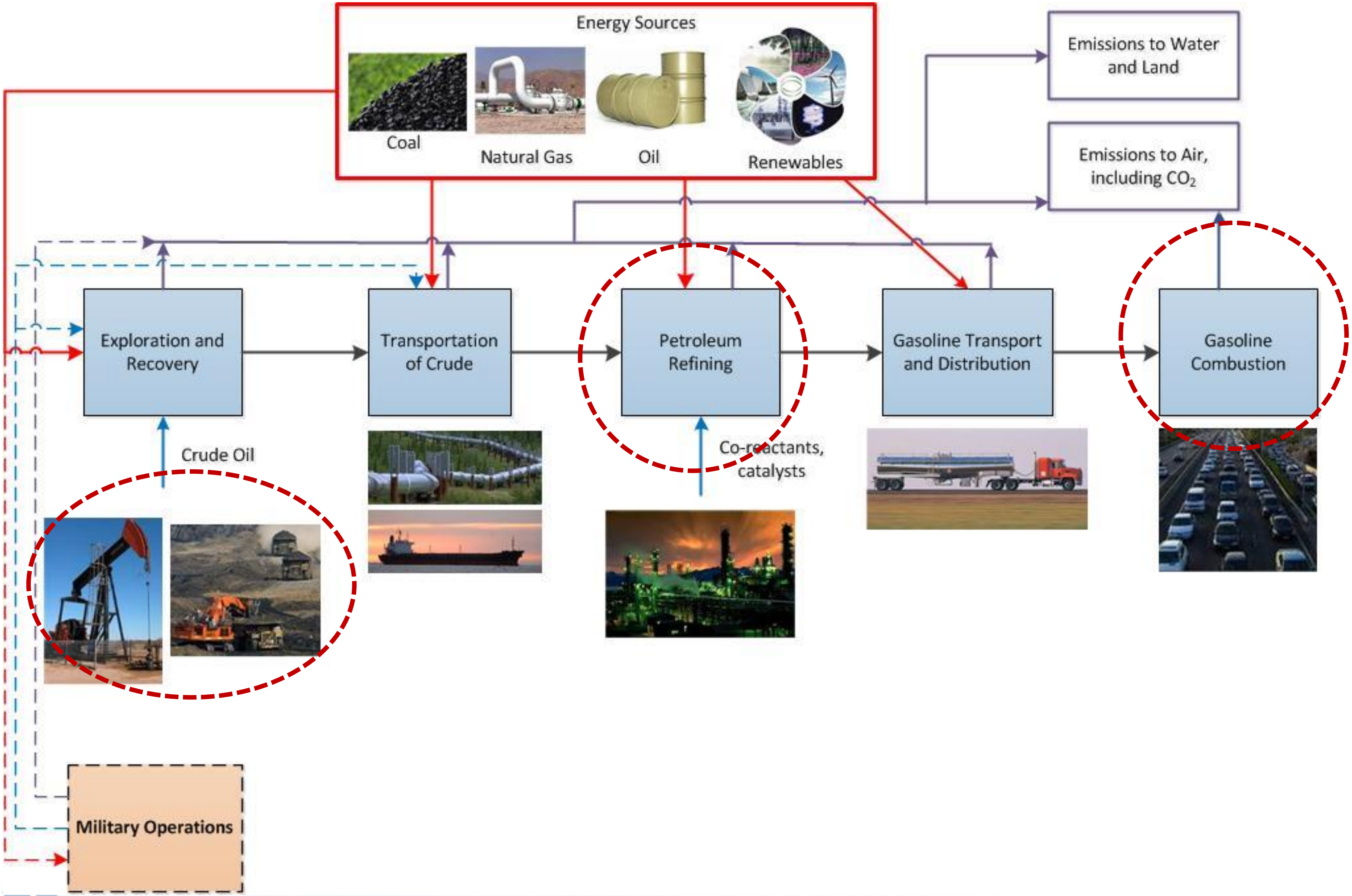
GREET data sources

- Baseline technologies and systems
  - EIA data and AEO projections
  - EPA eGrid for electric systems
  - USGS for water data
- Field operation data:
  - Oil sands and shale oil operations
  - Ethanol plants energy use
  - Farming data from USDA
- Collaboration with other national laboratories (e.g., TEAs by H2A models)
- Simulations with models:
  - ANL Autonomie for fuel economy
  - EPA MOVES for vehicle emissions, EPA AMPD for stationary emissions
  - LP models for refinery operation
  - Dispatch models for electricity marginal analysis
- Industry input:
  - Fuel producers and technology developers on fuels
  - Automakers and system components producers on vehicles

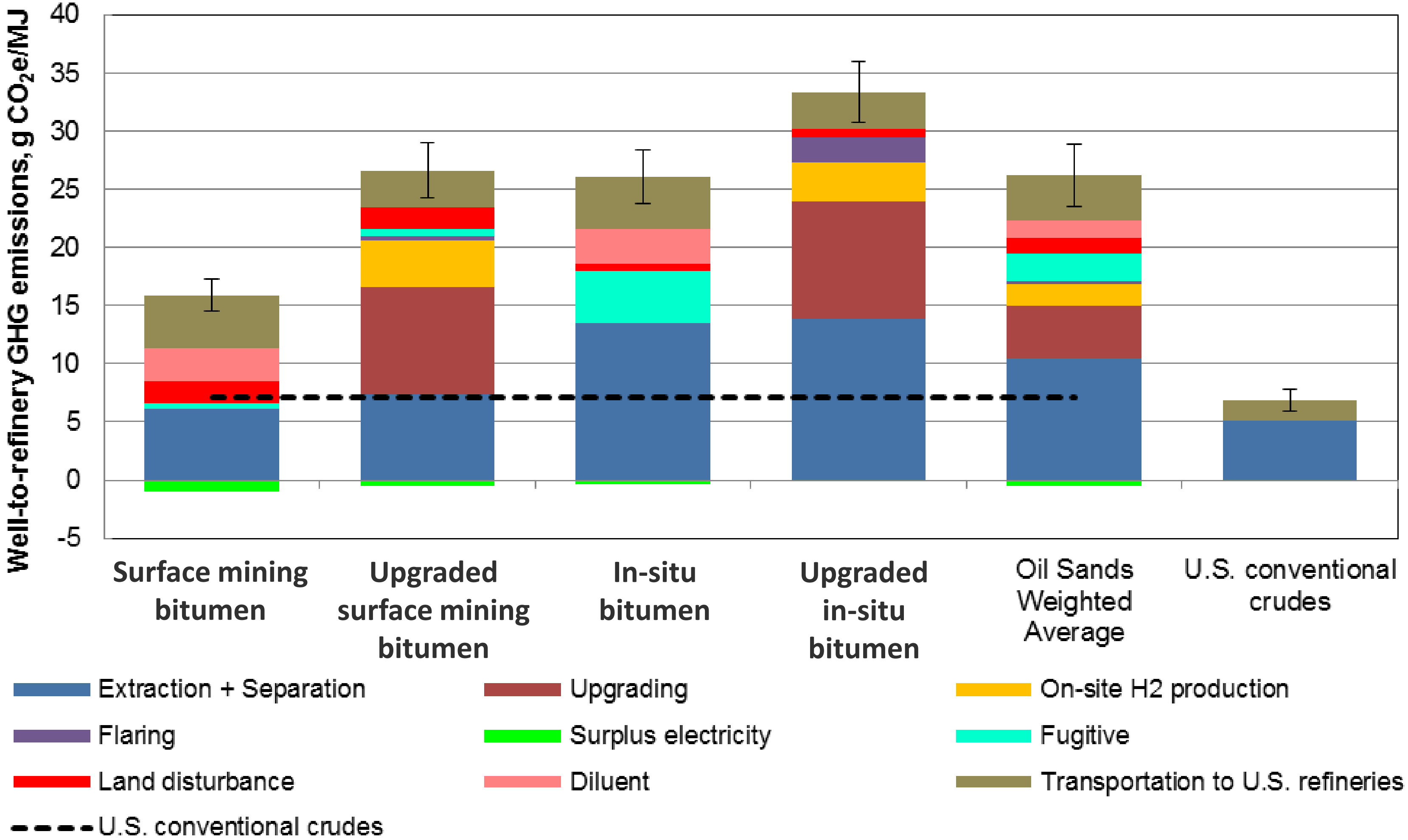
Main LCA issues and limitations

- LCA system boundary – scope of LCA
  - Process-based LCA
  - Attributional vs. consequential LCA
    - Average vs. marginal analysis
- Co-product methods in LCA
- Data availability and representation
  - Temporal variation
  - Geographic/spatial variation
  - Data uncertainty (e.g., methane emissions, LUC)
- Limitations: LCA does not inform about
  - Current vs. future technologies
  - Different TRL across processes and pathways
  - Resource and infrastructure availability
  - Economics, production scalability, and market acceptance/ competitiveness

LCA system boundary: petroleum to gasoline



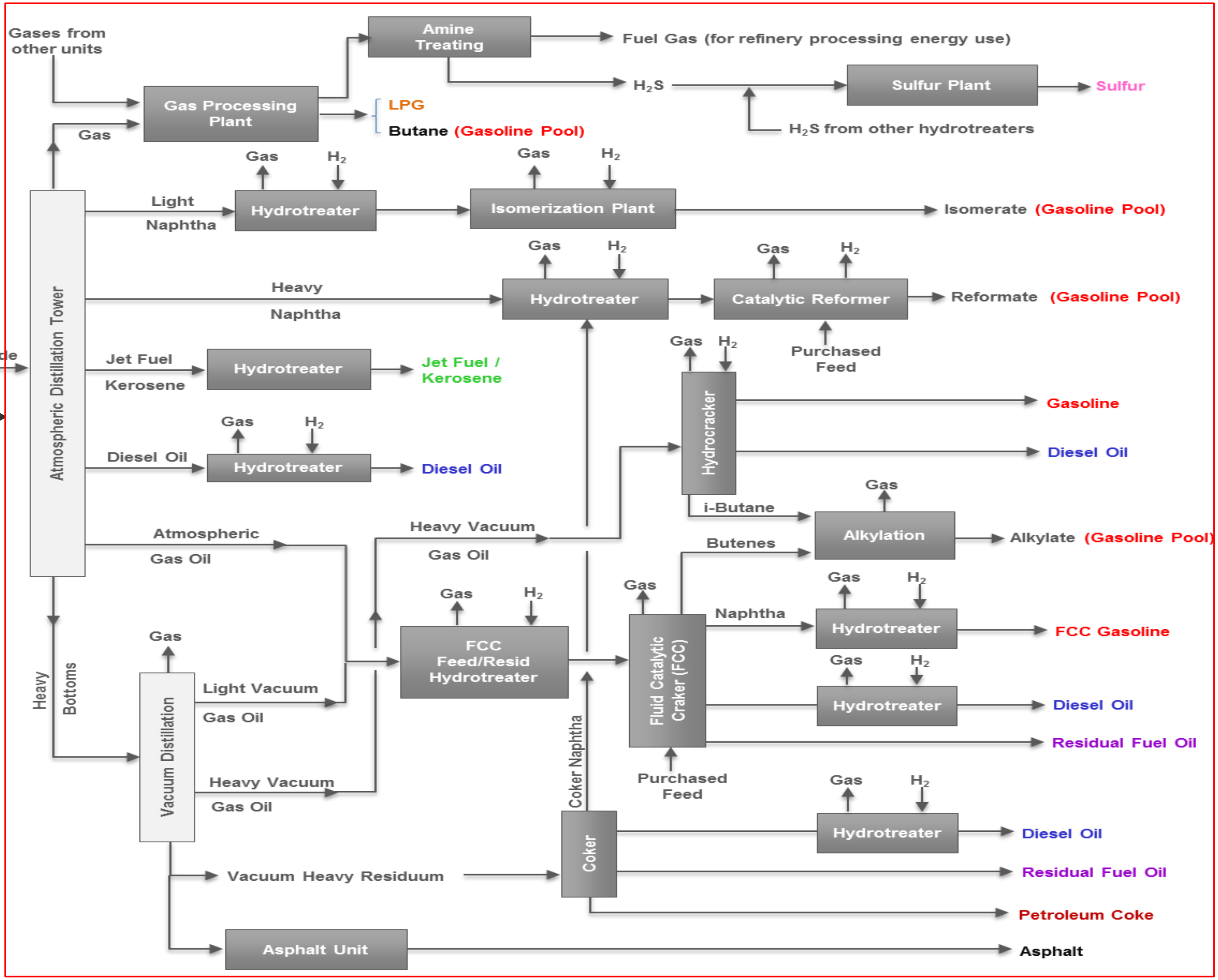
GHG Emissions of 27 Major Oil Sands Projects



Oil sand operations are 3 to 6 times more carbon intensive than average US conventional crudes

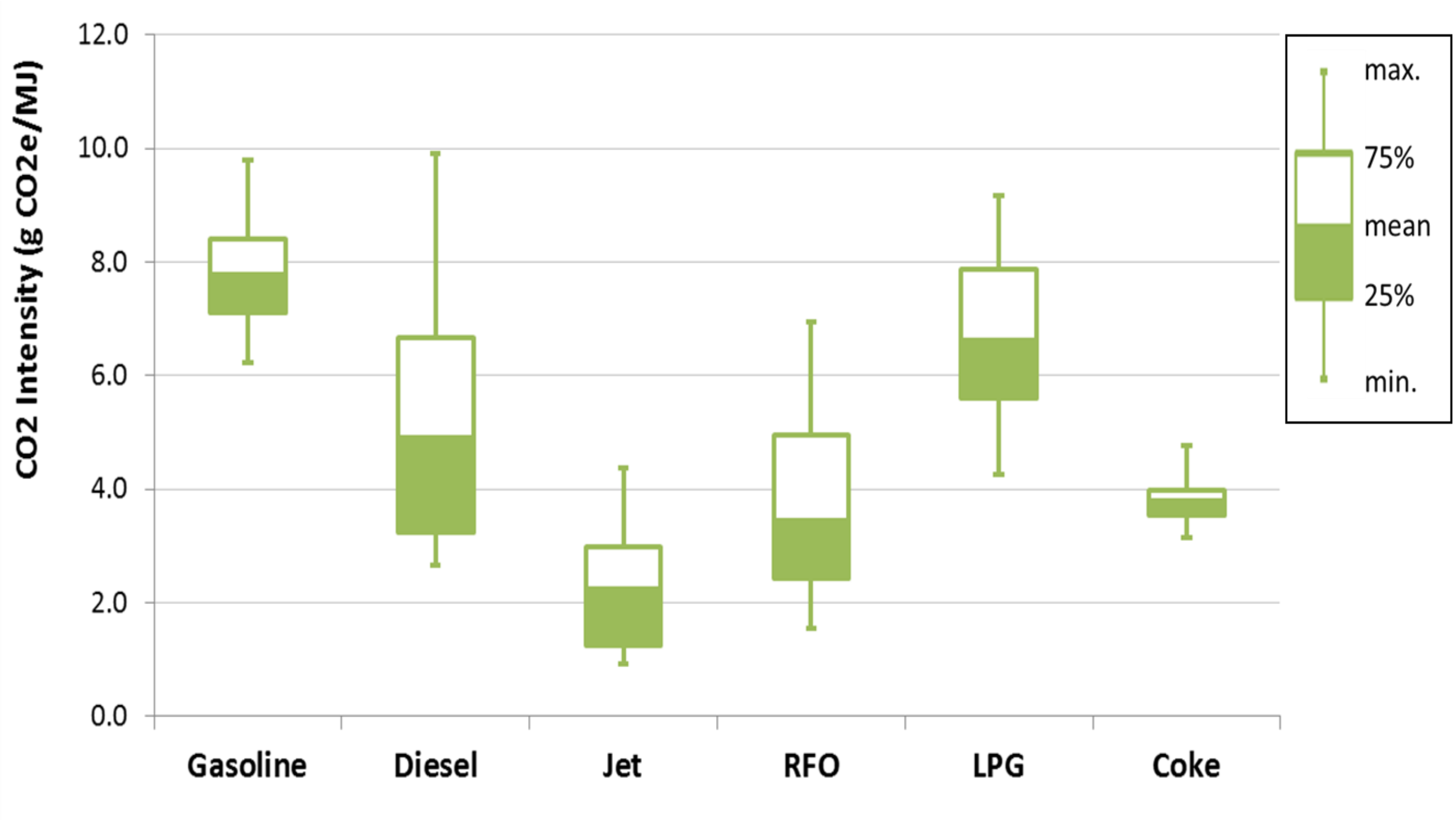
http://pubs.acs.org/doi/abs/10.1021/acs.est.5b01255

Refinery Analysis -Data are key for proper LCA



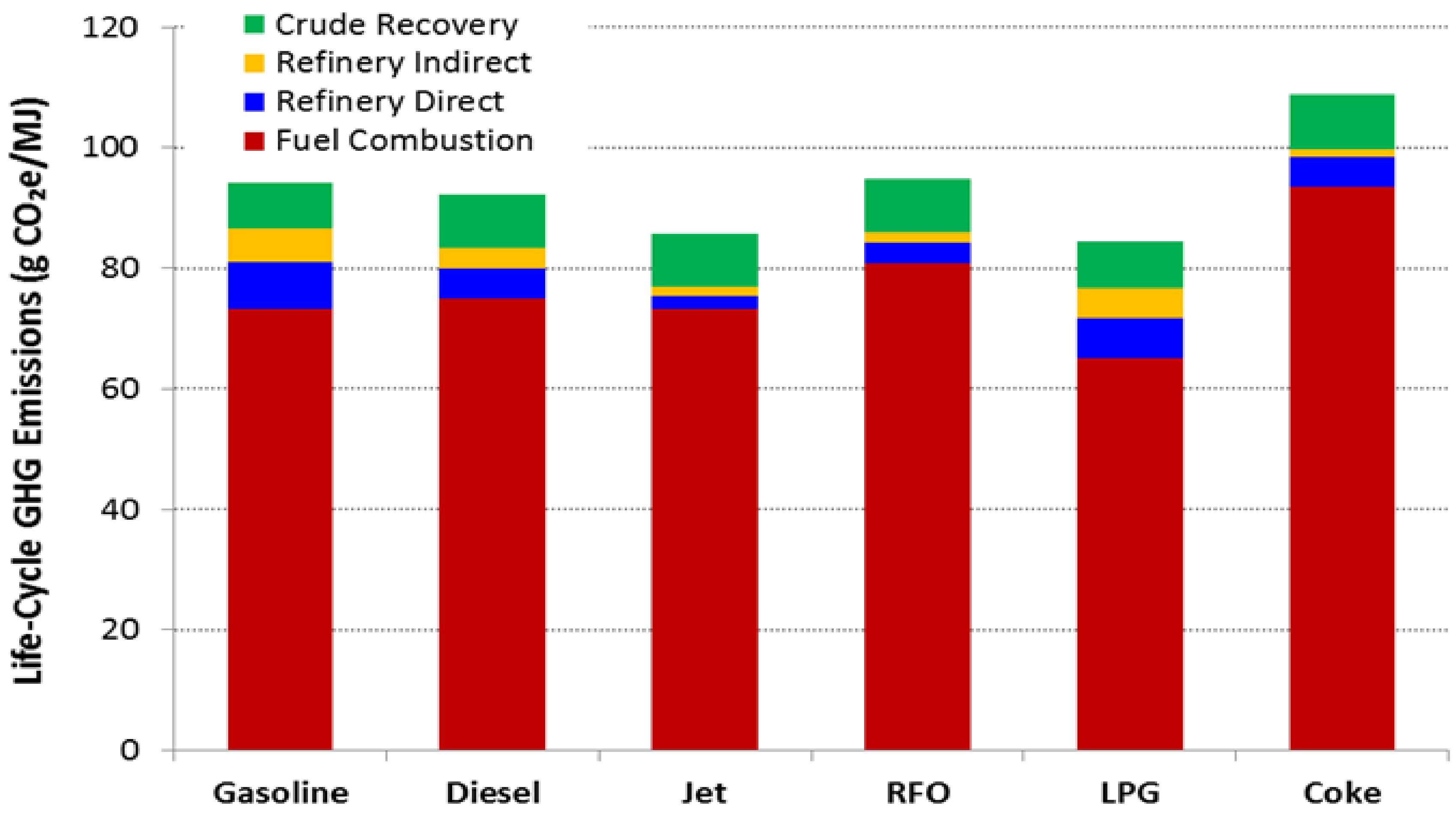
-Other feed/blends
-Process fuels
-Utilities

Developed refinery products CO_2 intensity with data from 43 large U.S. refineries (~70% U.S. refining capacity)

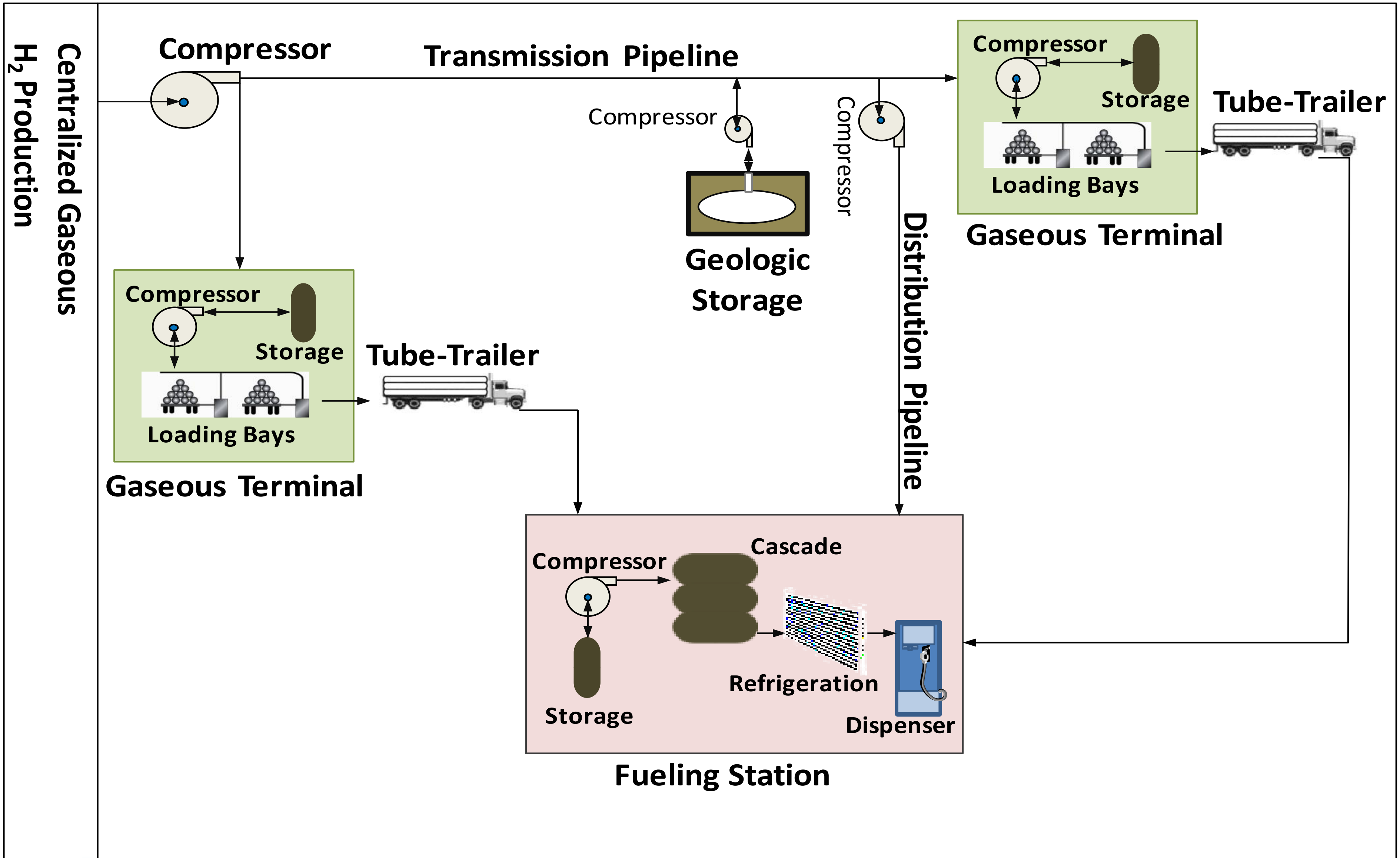


- ✓ Elgowainy et al. *Environmental Science and Technology*, 2014
- ✓ Forman et al. *Environmental Science and Technology*, 2014
- ✓ Han et al. *Fuel*, 2015

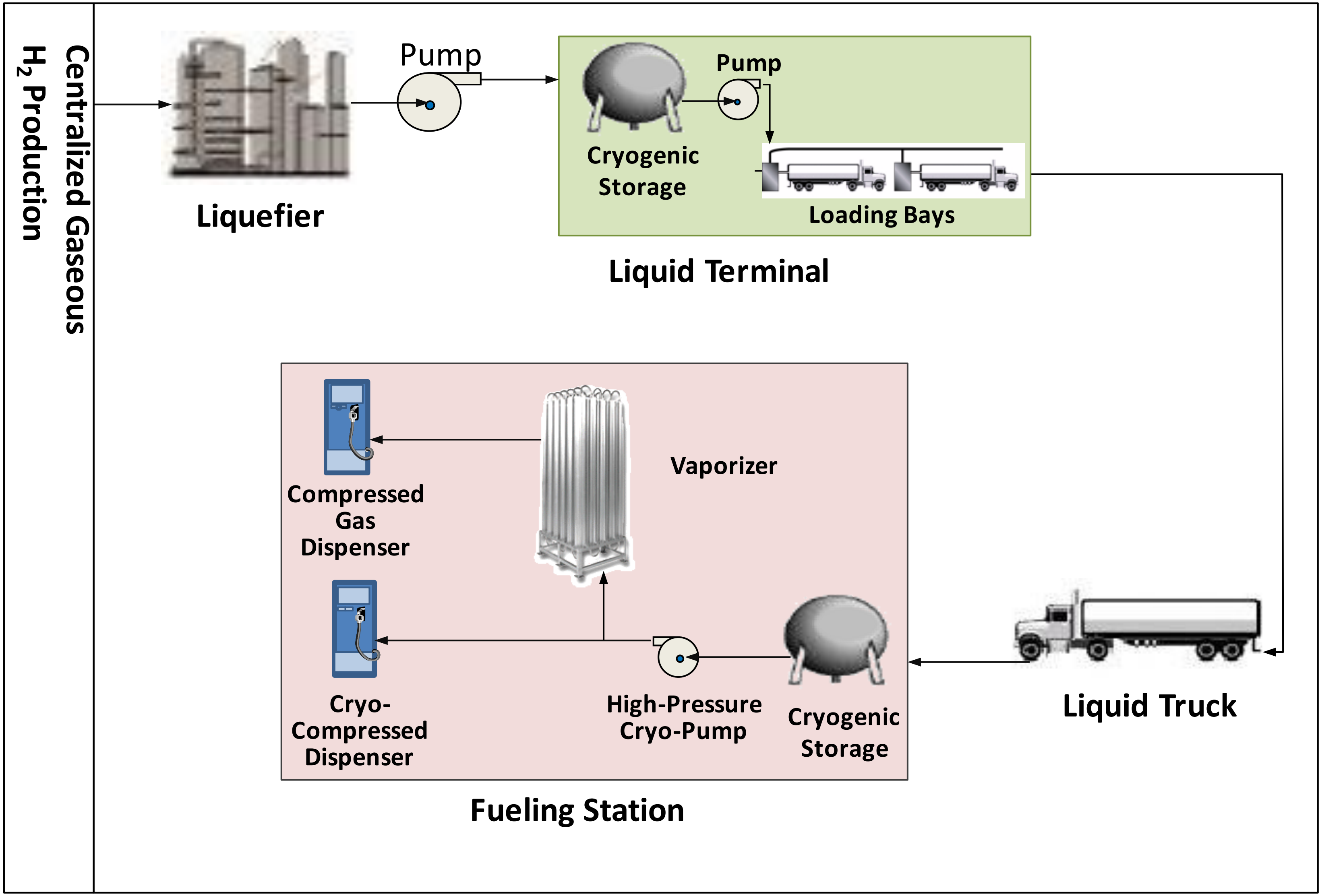
WTW GHG emissions of petroleum fuels is dominated by end use release of CO_2; refinery emissions is a distant second



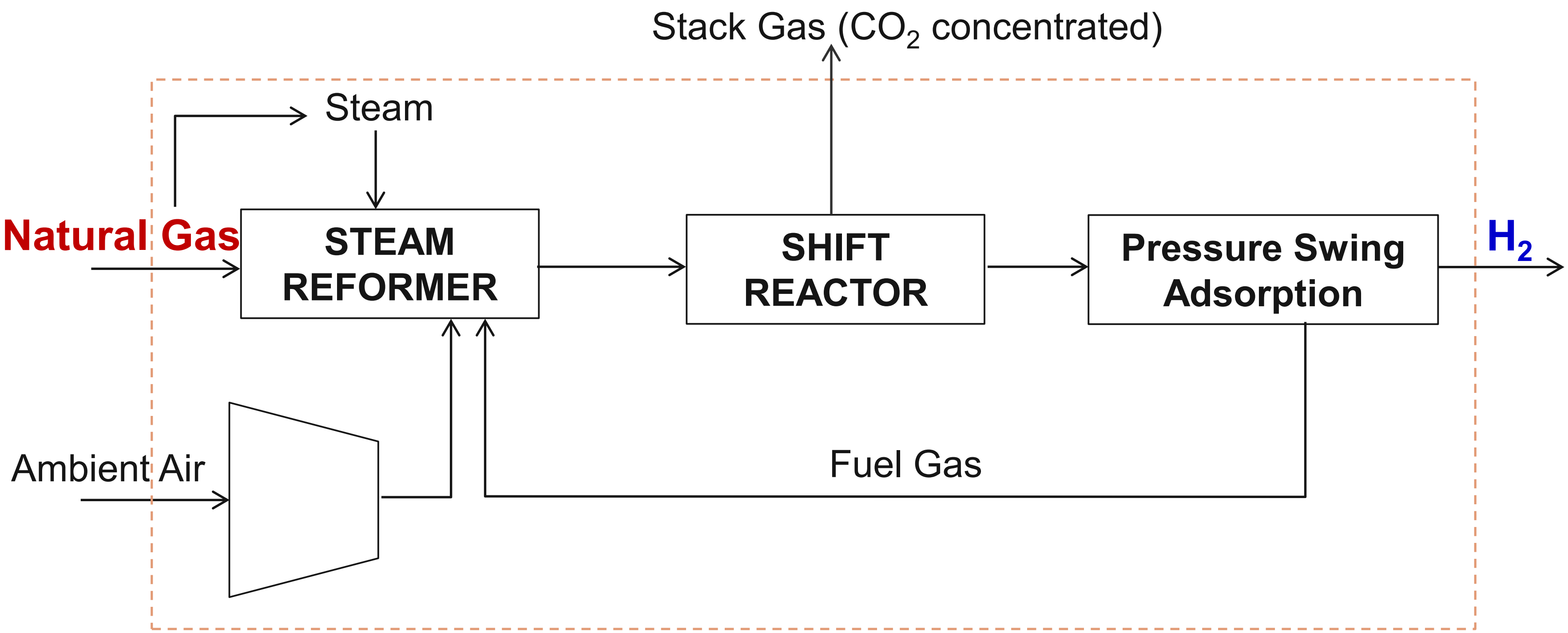
Production and delivery pathways of gaseous H_2



Production and delivery pathways for liquid H_2



Hydrogen production today is mainly from SMR, but other low-carbon pathways exist



At 72% NG to H_2 energy efficiency (LHV-basis)

→ 11 $kg_{CO_{2e}}/kg_{H_2}$

Energy use and GHG emissions are issues for liquefaction

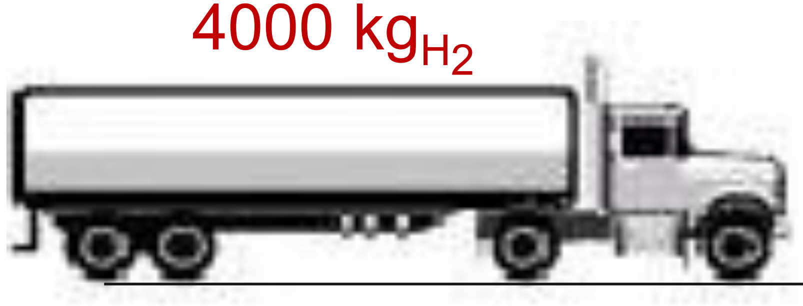
SMR-H_2 → 11 $kg_{CO_{2e}}/kg_{H_2}$

	GHG Emissions (g_{CO2e}/kWhe)	GHG Emissions (kg_{CO2e}/kg_{H2})*	Liquefaction Capacity (ton/day)
California	380	4.5	30
Louisiana	610	7.4	70
Indiana	1070	13	30
New York		0	40
Alabama	580	7.0	30
Ontario	130	1.6	30
Quebec	20	0.20	27
Weighted Average		**5.0**	
If US mix	670	**8.0**	

*Assuming liquefaction energy of 12 kWhe/kg_H_2

GHG emissions of LH_2 truck delivery is smaller than tube-trailer delivery due to higher payload

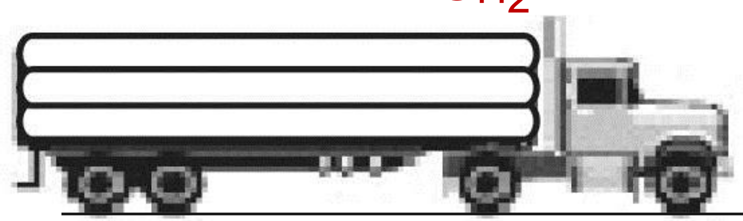
4000 kg_{H_2}



$0.1\ kg_{CO_{2e}}/kg_{H_2}$ ← 60 mi to city gate

$0.5\ kg_{CO_{2e}}/kg_{H_2}$ ← 300 mi to city gate

250 bar, 550 kg_{H_2}



$0.7\ kg_{CO_{2e}}/kg_{H_2}$ ← 60 mi to city gate

$3.5\ kg_{CO_{2e}}/kg_{H_2}$ ← 300 mi to city gate

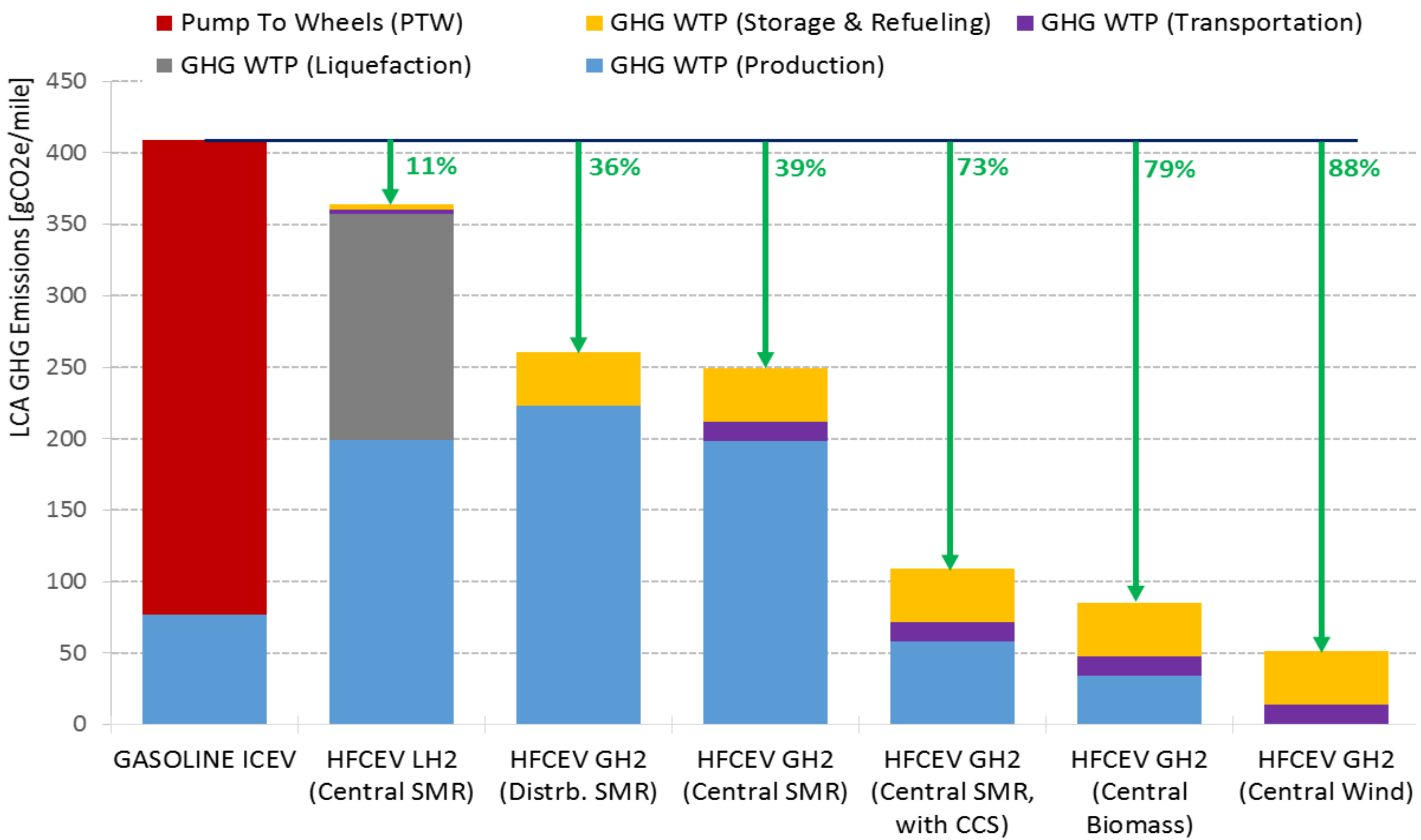
Fuel cycle GHG emissions of current LH_2 is comparable to compressed GH_2 pathways in the US with long T&D distances

$kg_{CO_{2e}}/kg_{H_2}$

Pathway	Production	Transport	Compression /liquefaction	Total
GH2 (700 bar)	11	0.7-3.5	3.0	**15 – 18**
LH2 (CcH2)	11	0.1-0.5	5.2 **or** **8.2‡**	**16 – 17** **or** **19 – 20‡**

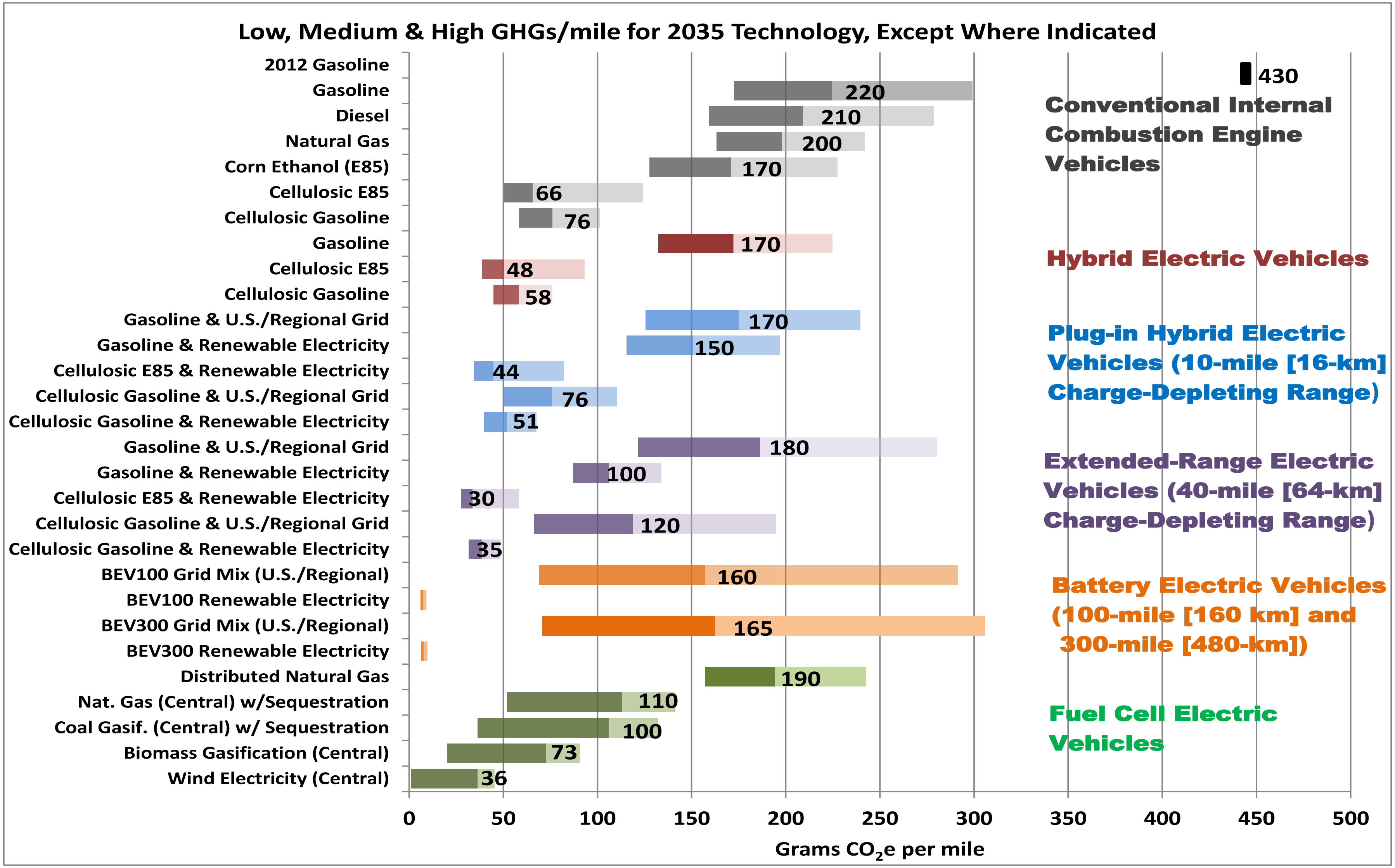
‡ Assuming US mix for H2 liquefaction

GHG emissions reduction potential of H_2 FCVs depends on H_2 production and packaging for delivery and refueling



Assuming 26 mpg for gasoline ICEV and 55 mpgge for H_2 FCEV

WTW GHG Emissions in g CO_{2e}/mile: 2035 Mid-Size Car



Low/high band: sensitivity to uncertainties associated with projected fuel economy values and selected fuel pathway parameters

(DOE EERE April 25 2013, Record 13005)

Please visit http://greet.es.anl.gov for:

- *GREET models*
- *GREET documents*
- *LCA publications*
- *GREET-based tools and calculators*