GREET Life-Cycle Analysis Model and Key LCA Issues for Vehicle/Fuel Technologies

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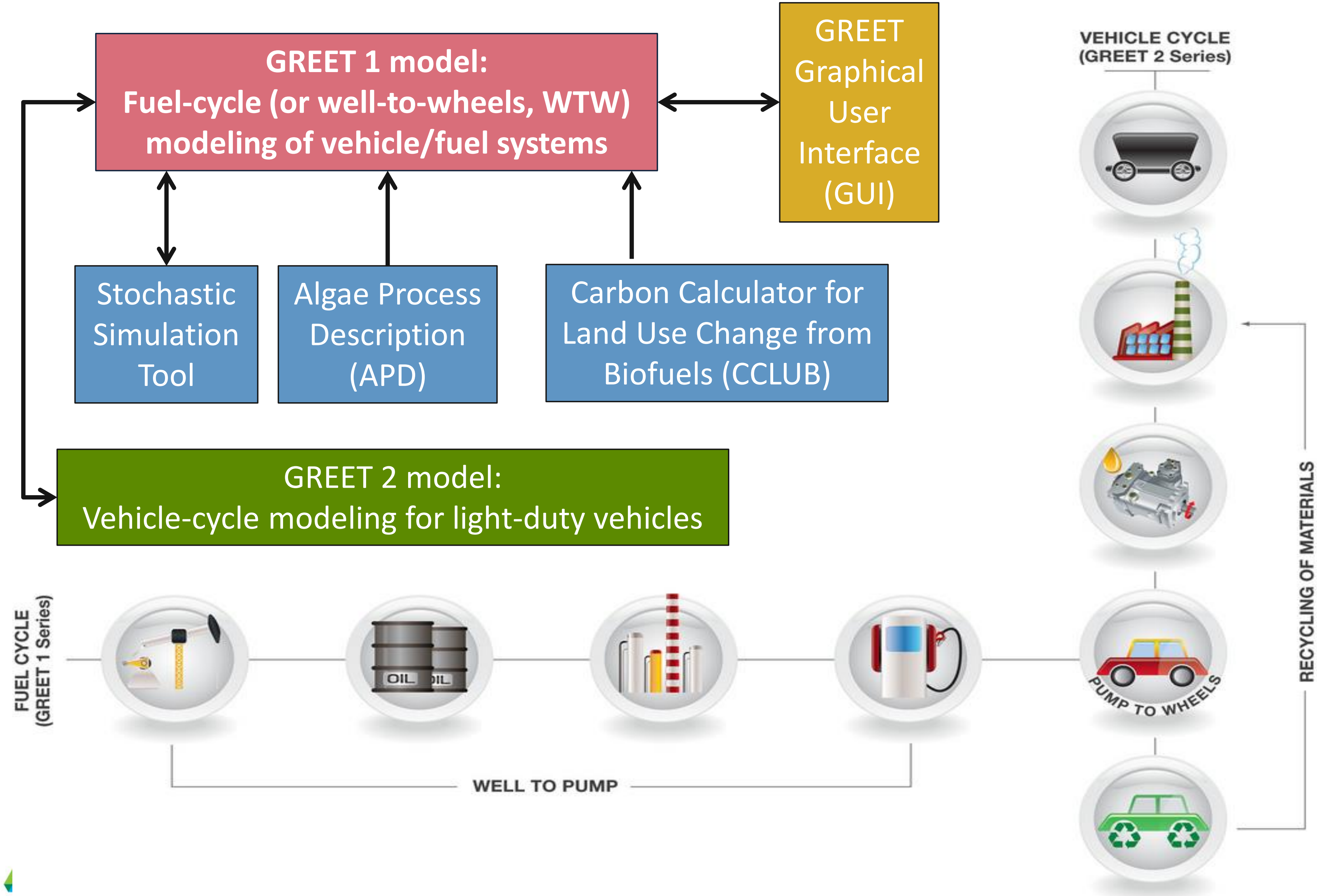
The GREET™ (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) Model



GREET and its publications are available at greet.es.anl.gov

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GREET Model

The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model

GREET News

GREET.net 2014

Oct 3, 2014

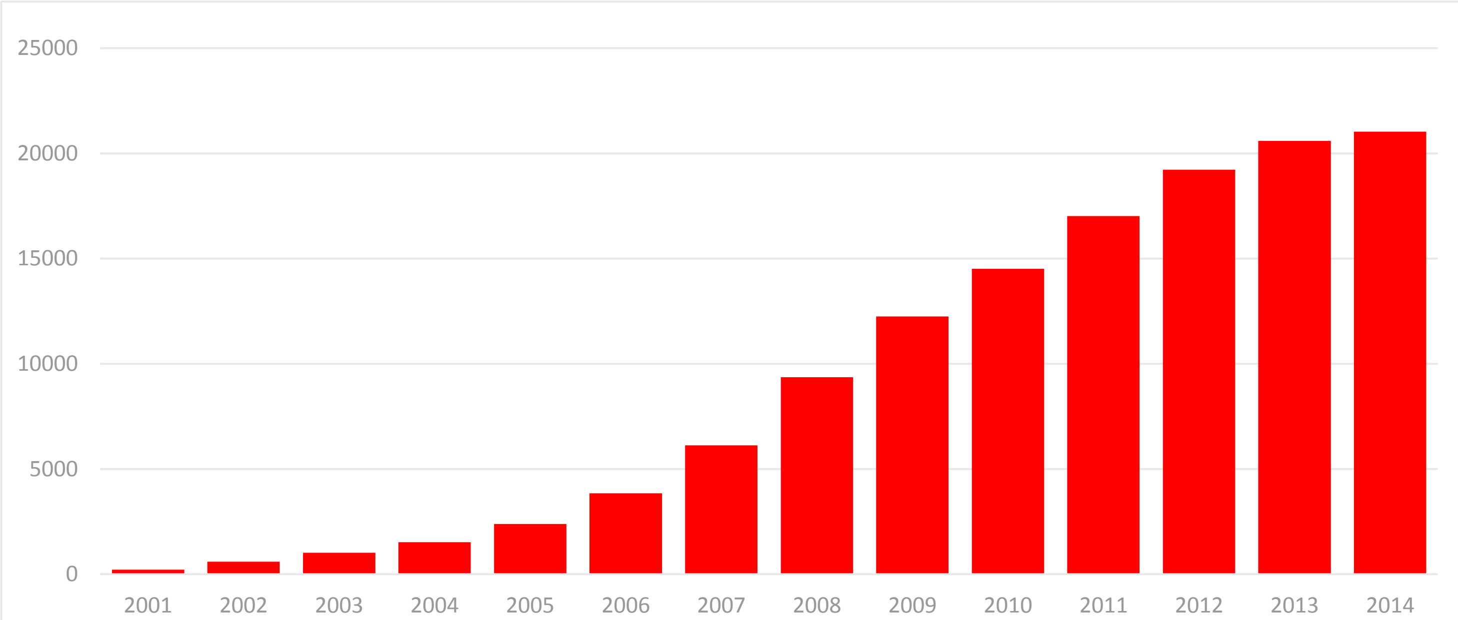
GREET LIFE-CYCLE MODEL

The latest major update was developed in order to be more robust and flexible. The major additions to the GREET 2014 version are:

- Updated pathway structure to allow more complex and detailed pathways
- Updated processes to allow multiple input and multiple outputs, each allocated output can be used downstream
- Updated vehicle results to allow multiple functional units
- Incorporated charting tool
- Incorporated CCLUB with two new feedstocks (poplar and willow), new organic carbon emission factors for soil depth of 100 cm, and new land-use change results
- Incorporated marine vessel module
- Added water consumptions for the major pathways as an additional life-cycle analysis metric
- Added black carbon and organic carbon emissions as an additional criteria air pollutants (CAP) and GHG species
- Updated refining efficiency and greenhouse gas (GHG) emission intensity of petroleum products
- Expanded oil sands modeling with more detailed and refined operation data
- Updated methane emission for natural gas pathways as well as petroleum venting, fugitive and flaring emissions
- Updated soybean and biodiesel production assumptions
- Added pretreatment pathways including dilute acid pretreatment and ammonia fiber expansion
- Added conventional and bio-product pathways
- Added catalyst production pathways
- Updated enzyme and yeast assumptions
- Updated global warming potential (GWP)
- Other updates are in progress and notification will be provided when these updates become available.

Download GREET.net from the GREET.net website

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, hydro-power, wind power, and solar energy
- **Greenhouse gases (GHGs)**
  - CO_2, CH_4, N_2O, and black carbon
  - CO_2e of the four (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 mile driven
  - Per unit of energy (million Btu, MJ, gasoline gallon equivalent)
  - Other units (such as per ton of biomass)

GREET covers on-road, air, marine, and rail transportation

- Over 100 fuel production pathways are covered
  - Petroleum based
  - Natural gas based
  - Renewable fuels
  - Electricity
  - Hydrogen
- On-road transportation: light and heavy vehicles
  - Internal combustion engines
  - Hybrid electric vehicles
  - Battery electric vehicles
  - Fuel cell vehicles
- Air transportation
  - Globally, a fast growing sector with GHG reduction pressure
  - Interest by ICAO, U.S. FAA, and commercial airlines
  - GREET includes
    - Passenger and freight transportation
    - Various alternative fuels blending with petroleum jet fuels
- Marine transportation
  - Pressure to control air pollution in ports globally
  - Interest by IMO, U.S. EPA, local governments
  - Biodiesel and LNG are potential marine alternative fuels
  - GREET includes
    - Ocean and inland water transportation
    - Baseline diesel and alternative marine fuels
- Rail transportation
  - Interest by U.S. DOT, railroad companies
  - Potential for CNG/LNG to displace diesel

Approach, data sources, and key issues with GREET LCA

- **Approach: build LCA modeling capacity with the GREET model**
  - Build a consistent LCA platform with reliable, widely accepted methods/protocols
  - Address emerging LCA issues
  - Maintain openness and transparency of LCAs by making GREET publicly available
- **Data Sources**
  - Open literature and results from other researchers
  - Simulations with models such as ASPEN Plus for fuel production and ANL Autonomie and EPA MOVES for vehicle operations
  - Fuel producers and technology developers for fuels and automakers and system components producers for vehicles
  - Baseline technologies and energy systems: EIA AEO projections, EPA eGrid for electric systems, etc.
  - Consideration of effects of regulations already adopted by agencies

Main technical issues of LCAs

- LCA system boundary – scope of LCA
  - Process-based LCA
  - Attributional vs. consequential LCA
- Co-product methods in LCA
- Data availability and representation
  - Temporal variation
  - Geographic variation
  - Sensitivity of LCA parameters and uncertainty analysis

Co-product methods: benefits and issues

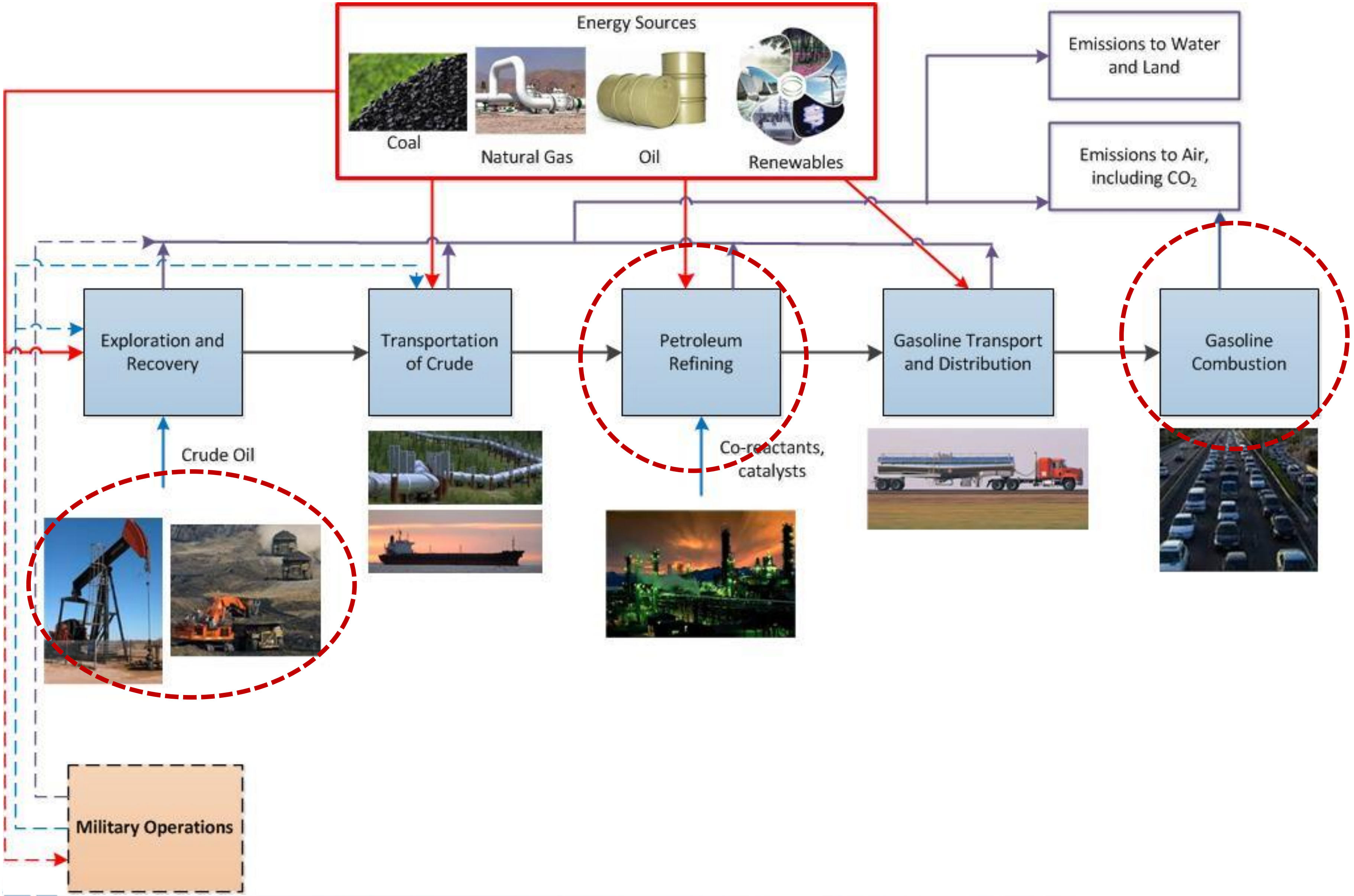
- Displacement method
  - Data intensive: need detailed understanding of the displaced product sector
  - Dynamic results: subject to change based on economic and market modifications
- Allocation methods: based on mass, energy, or market revenue
  - Easy to use
  - Frequent updates not required for mature industry, e.g. petroleum refineries
  - Mass based allocation: not applicable for certain cases
  - Energy based allocation: results not entirely accurate, when coproducts are used in non-fuel applications
  - Market revenue based allocation: subject to price variation
- Process energy use approach
  - GREET method for petroleum refineries
  - Detailed engineering analysis is needed
  - Upstream burdens still need allocation based on mass, energy, or market revenue

Wang et al. (2011) in *Energy Policy*

Co-Products and Their Treatment in GREET LCAs

Pathway	Co-Product	Displaced Products	LCA Method in GREET	Alternative LCA Methods Available in GREET
Corn ethanol	DGS	Soybean, corn, and other animal feeds	Displacement	Allocation based on market revenue, mass, or energy
Sugarcane ethanol	Electricity from bagasse	Conventional electricity	Allocation based on energy	Displacement
Cellulosic ethanol (corn stover, switchgrass, and miscanthus)	Electricity from lignin	Conventional electricity	Displacement	Allocation based on energy
Petroleum gasoline	Other petroleum products	Other petroleum products	Allocation at refining process level based on energy	Allocation based on mass, market revenue

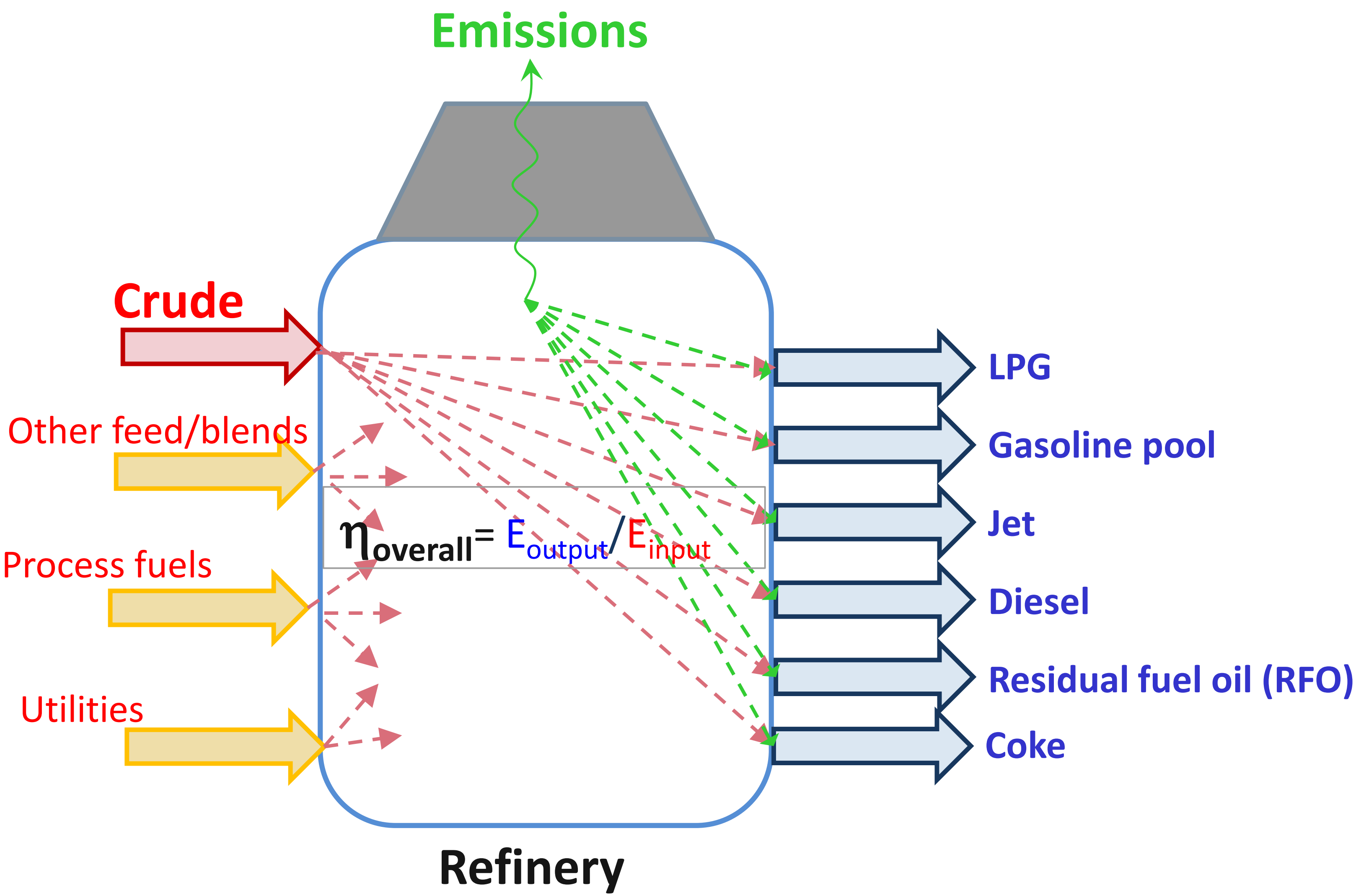
LCA system boundary: petroleum to gasoline



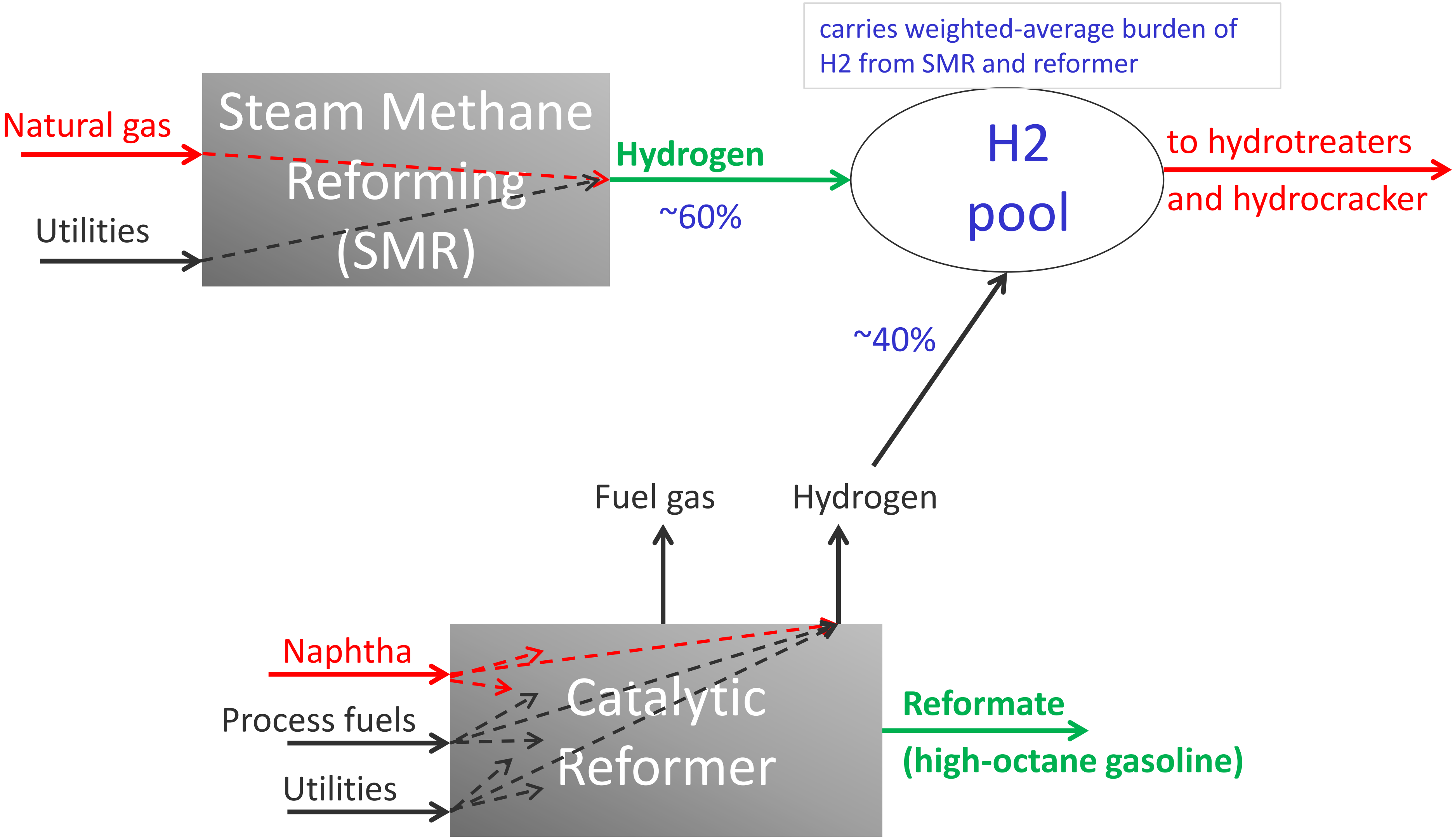
Indirect effects and land disturbance of petroleum fuels

- US military operations in the Middle East vs. petroleum geopolitics
  - Multi-purposes of military operations
    - What military operations to be included?
    - How to allocate total emission burdens over different purposes?
  - Marginal crude (Middle East crude) vs. average US crude (domestic vs. total import vs. Middle East import)
    - 8-18 g/MJ over US import of ME oil (Liska and Perrin 2010)
    - 1-2 g/MJ over total US crude use (Liska and Perrin 2010)
- Land disturbance (and reversion) of petroleum recovery
  - Exploration, drilling, and recovery
  - Pipelines (and rail)
  - Large amount of crude can be produced from a unit of land cover (relative to biofuel land footprint)
  - Allocation methods
    - Pay as you go
    - Amortization over lifetime
- Facility construction: US refineries were built 50 years ago; retroactive allocation of historical emissions to current fuel production?

Multiple products from refineries: overall refinery efficiency as well as product-specific efficiencies are determined

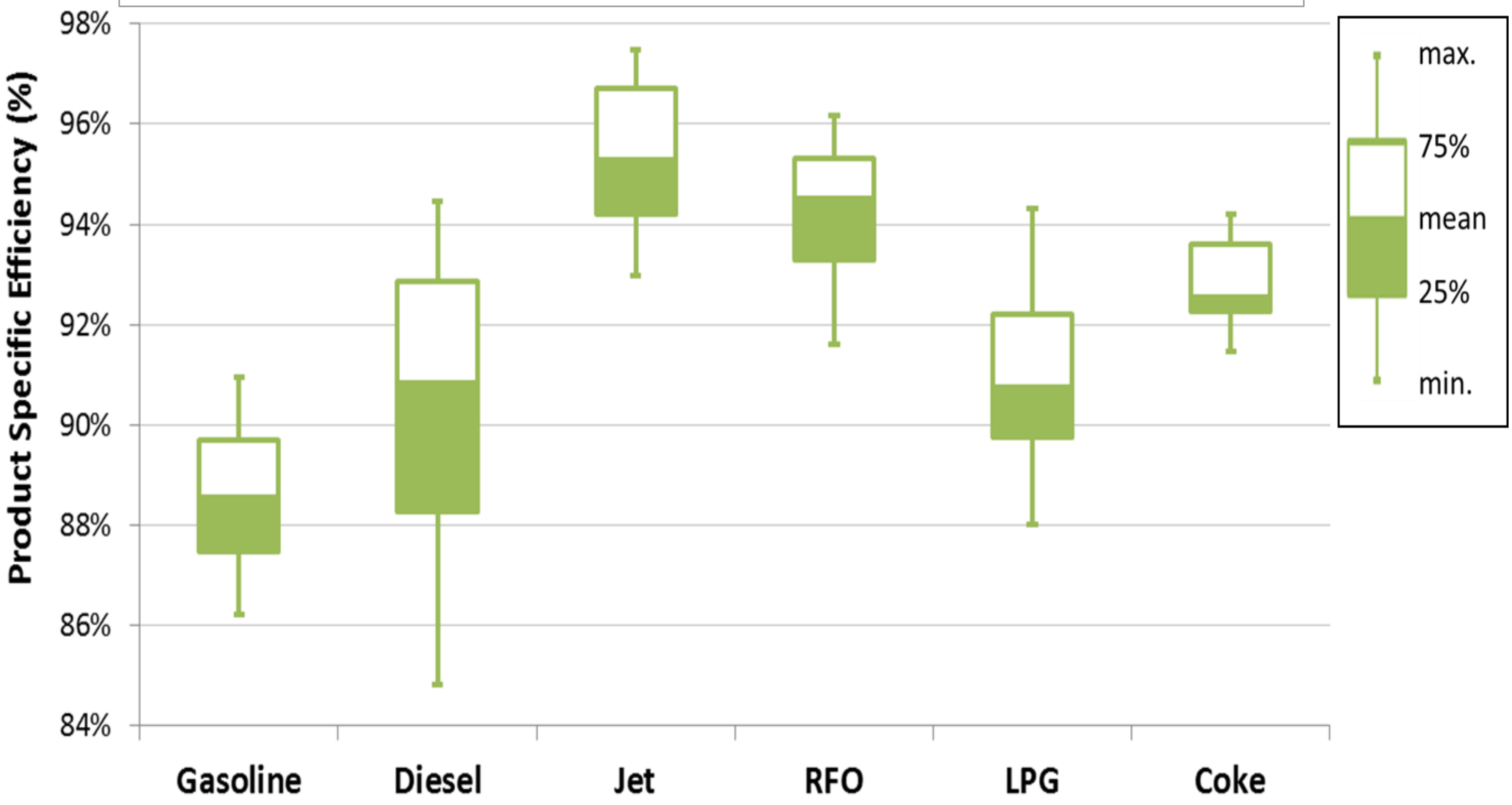


Allocation methodology of energy between products at process-unit level to make product pools (H2 pool as example)

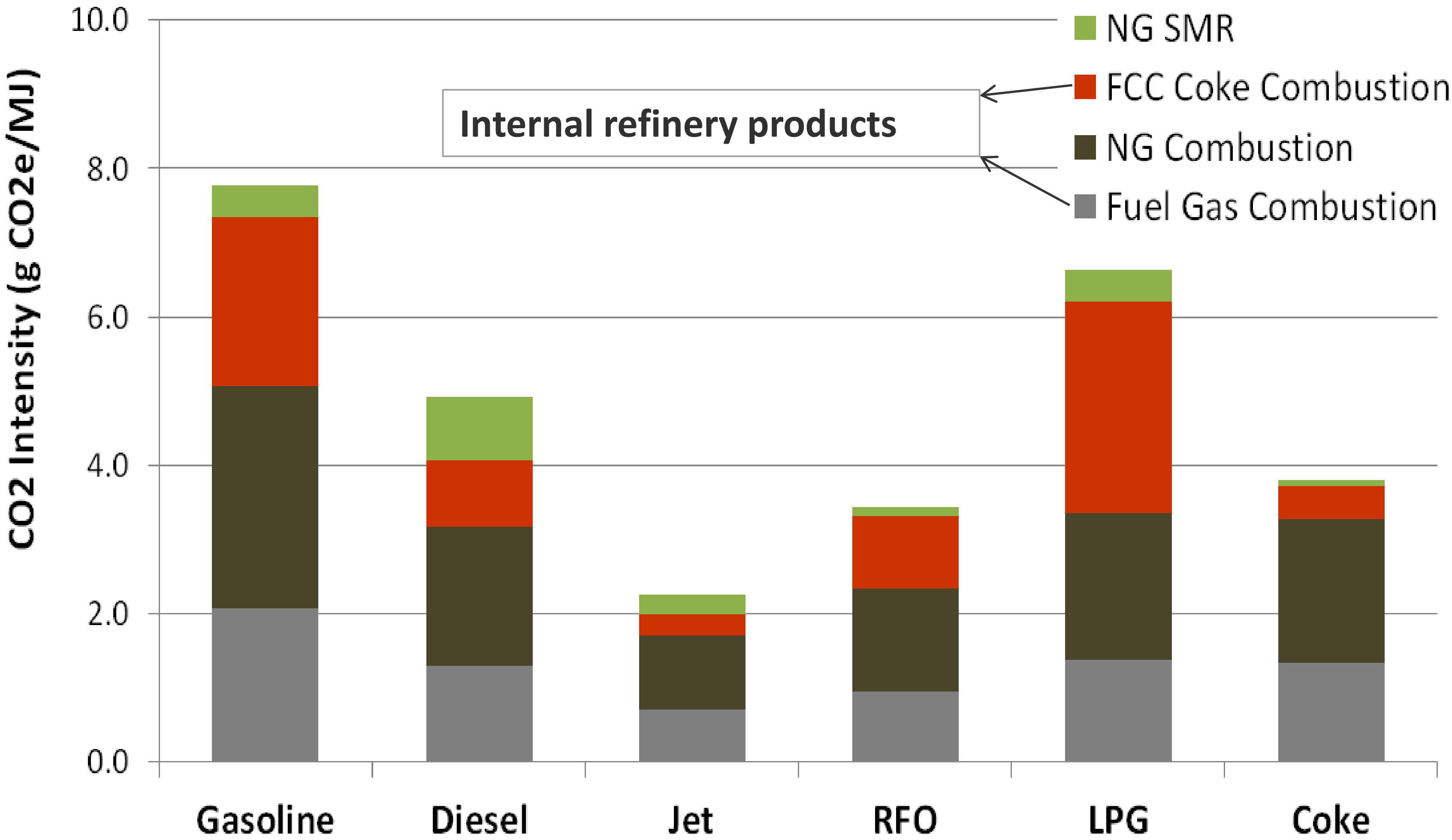


U.S. product-specific efficiency reflects the energy intensity of the refining units contributing to each product pool

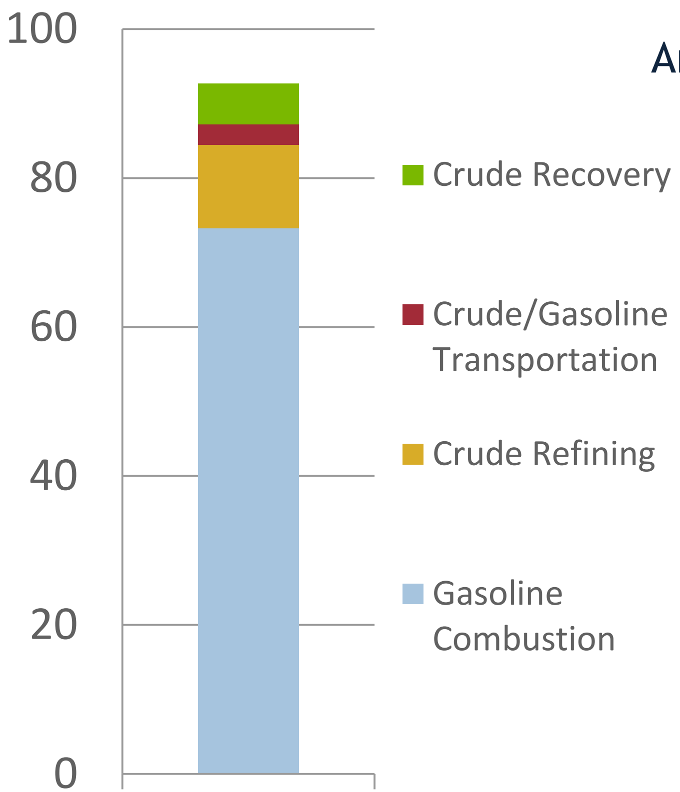
- Refining unit contributions to each pool vary among U.S. refineries
- Wider efficiency range for diesel compared to other products



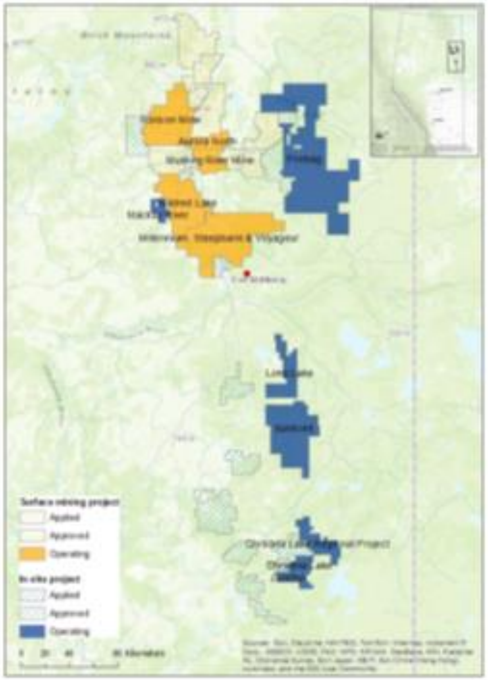
FCC coke, NG and fuel gas combustion are the major contributors to refinery products CO_2 intensity



Gasoline greenhouse gas emissions: grams/MJ



Argonne addressed GHG emissions of oil sands

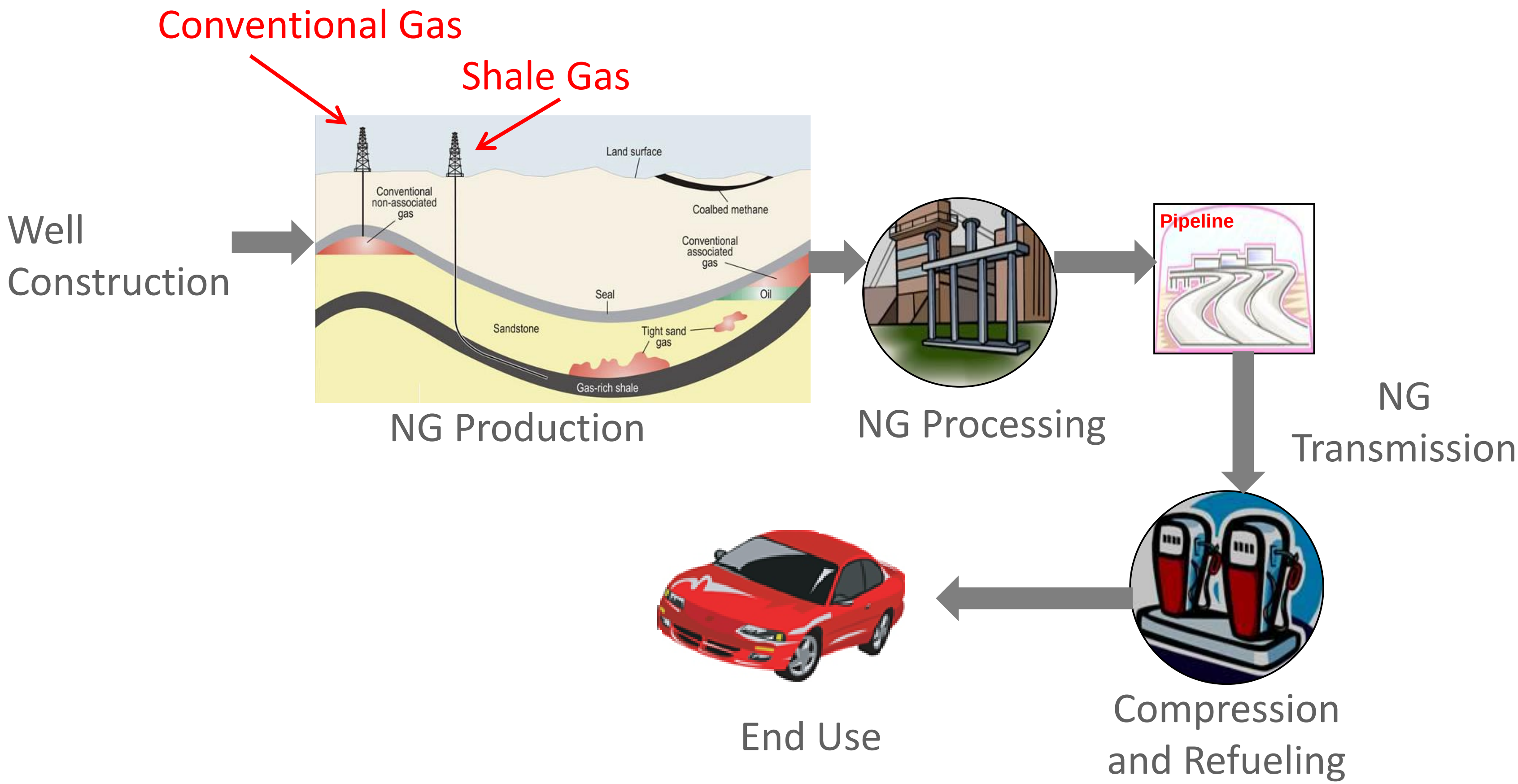


Oil sand land disturbance GHG (Yeh et al. 2014)

- Pay-as-you –go
  - ✓ 3.38-3.43 g/MJ for surface mining
  - ✓ 1.78-2.80 g/MJ for in-situ
- Amortization
  - ✓ 1.87-1.90 g/MJ for surface mining
  - ✓ 0.56-0.89 g/MJ for in-situ

	Conventional Crude	Mining SCO (53%)	Mining Dilbit (4%)	In-Situ SCO (8%)	In-Situ Dilbit (35%)
Recovery	4.13	19.6	6.95	24.0	12.7
Land Disturbance	—	1.86	1.47	0.70	0.56
Refining	15.3	18.2	16.9	19.1	18.5
Transport. & Distribution	2.3	3.7	3.9	3.7	3.9
Total WTP	**21.7**	**43.3**	**29.2**	**47.5**	**35.7**

LCA system boundary: compressed natural gas

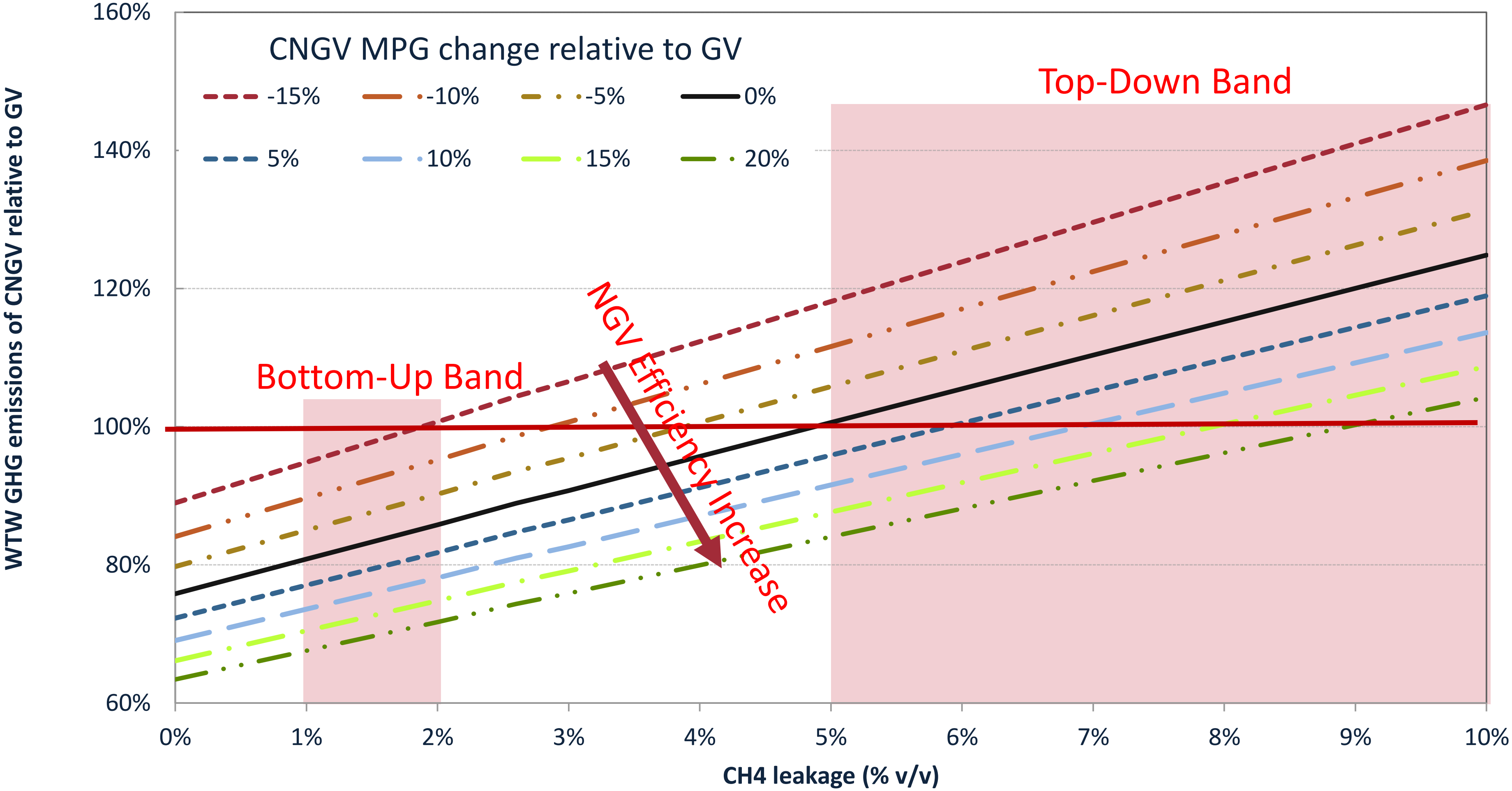


Methane leakage along NG supply chain is a major concern

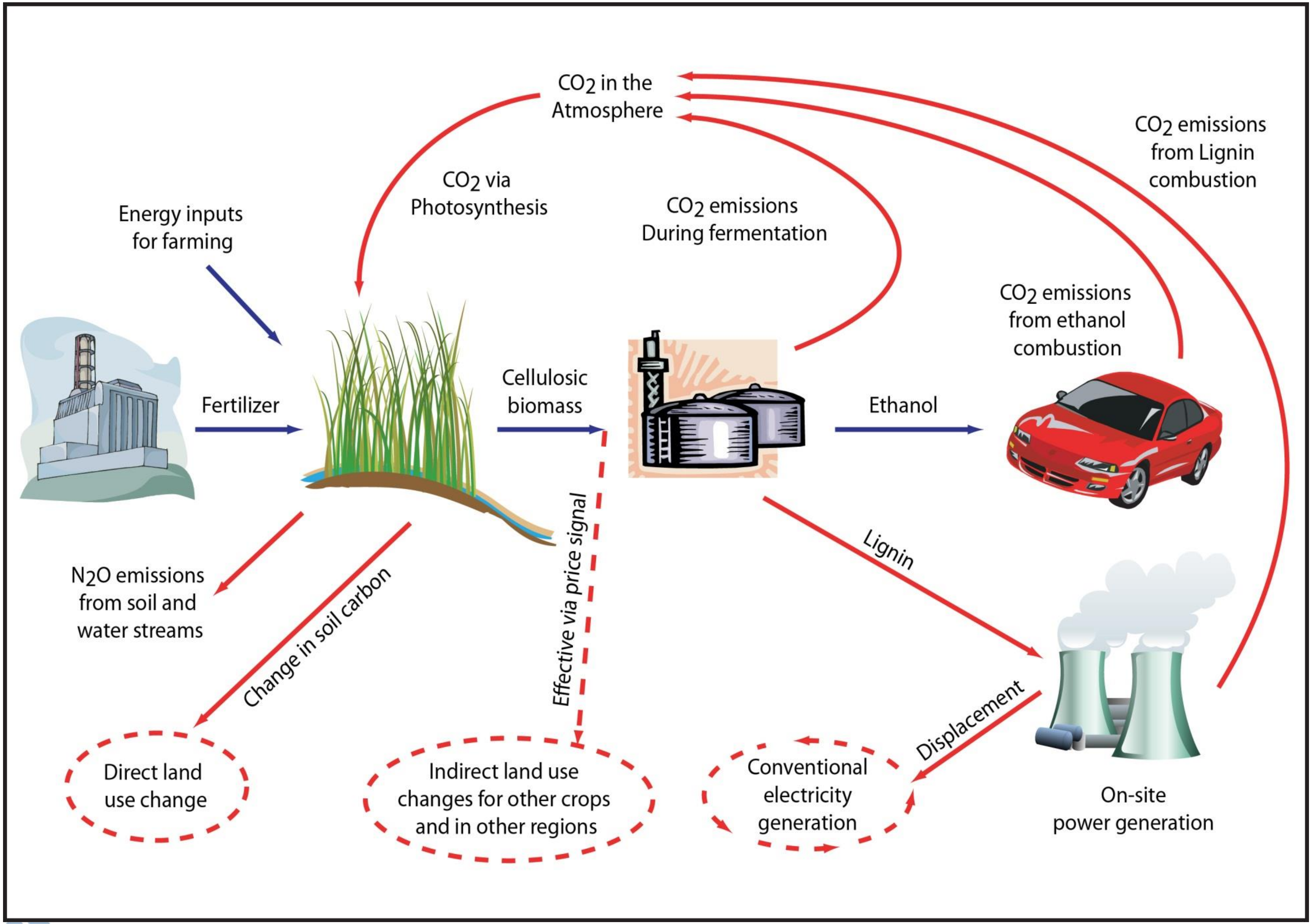
Sector	CH_4 Emissions: Percent of Volumetric NG Produced (Gross)											
	EPA - Inventory 5 yr avg (2011)	CMU - Marcellus Shale (2011)	NREL - Barnett Shale (2012)	API/ ANGA Survey (2012)	NOAA - DJ Basin (2012)	NOAA - Uintah Basin (2013)	Exxon Mobil (2013)	EPA - Inventory 2011 data (2013)	Univ. Texas (2013)	EPA - Inventory 2012 data (2014)	Stanford (2014)	IUP - Bakken (2014)	IUP - Eagle Ford (2014)
Gas Field	1.18		0.9	0.75	2.3-7.7	6.2-11.7	0.6	0.44	0.42	0.33		2.8-17.4	2.9-15.3
Completion/ Workover			0.7					0.17	0.03	0.04			
Unloading			0					0.04	0.05	0.05			
Other Sources			0.2					0.23	0.34	0.24			
Processing	0.16		0				0.17	0.16		0.15			
Transmission	0.38		0.4				0.42	0.34		0.35			
Distribution	0.26							0.23		0.21			
Total	1.98	2.2						1.17		1.03	3.6-7.1		

- Studies in **GREEN** are with bottom-up approach: measuring emissions of individual sources -> aggregating emissions along supply chain
- Studies in **RED** are with top-down approach: measuring CH4 concentration above or near fields/cities -> deriving CH4 emissions -> attributing emissions to NG-related activities

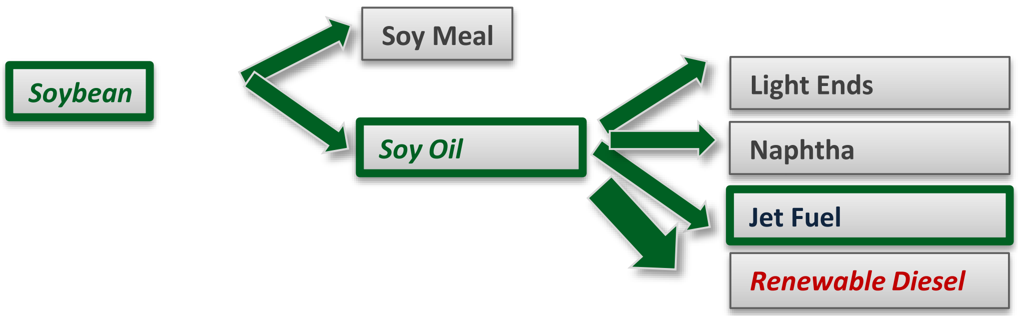
CNG vehicle efficiency and CH_4 leakage are two key factors of WTW GHG emissions of CNGVs vs. GVs



LCA system boundary: switchgrass to ethanol

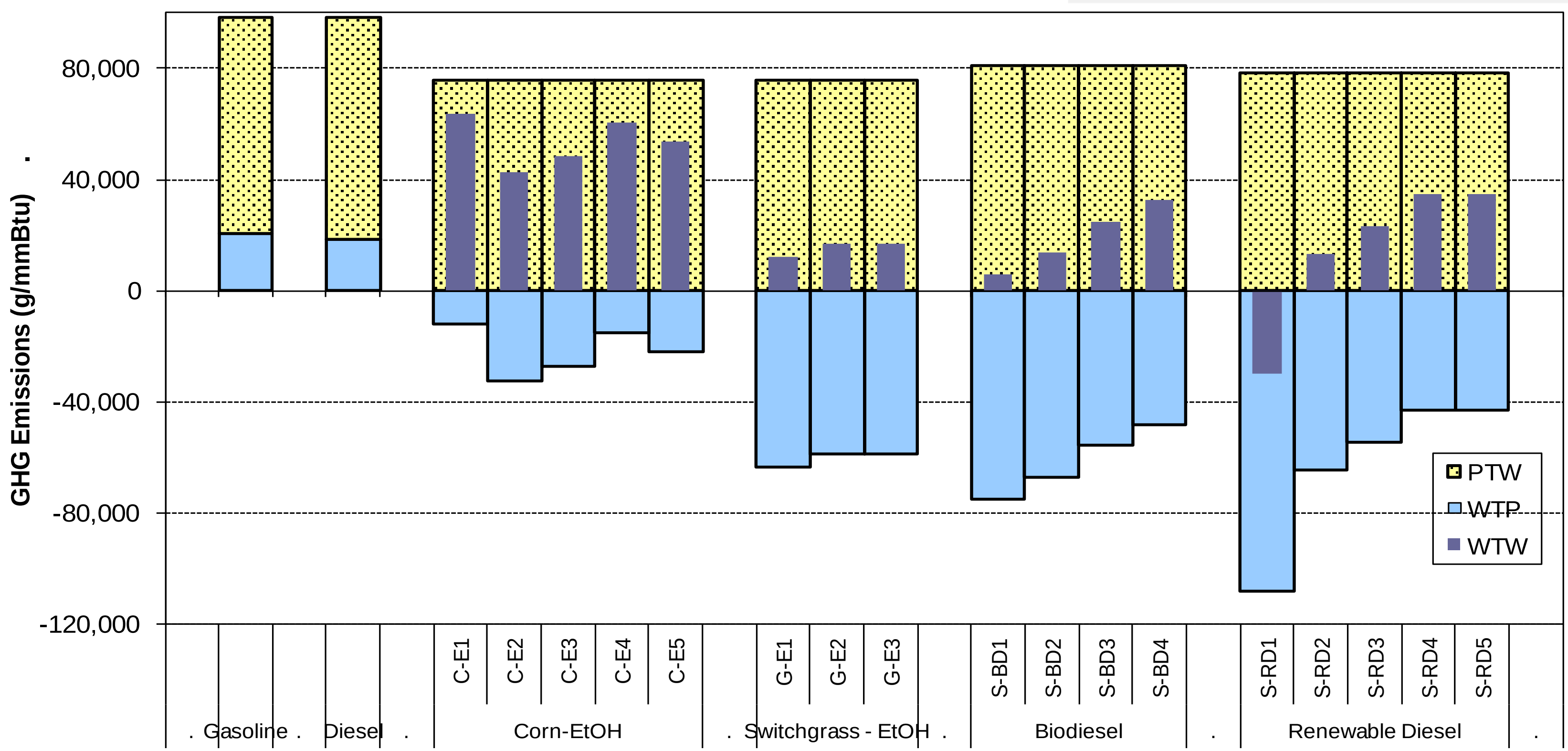


Choice of co-product methods can have significant LCA effects

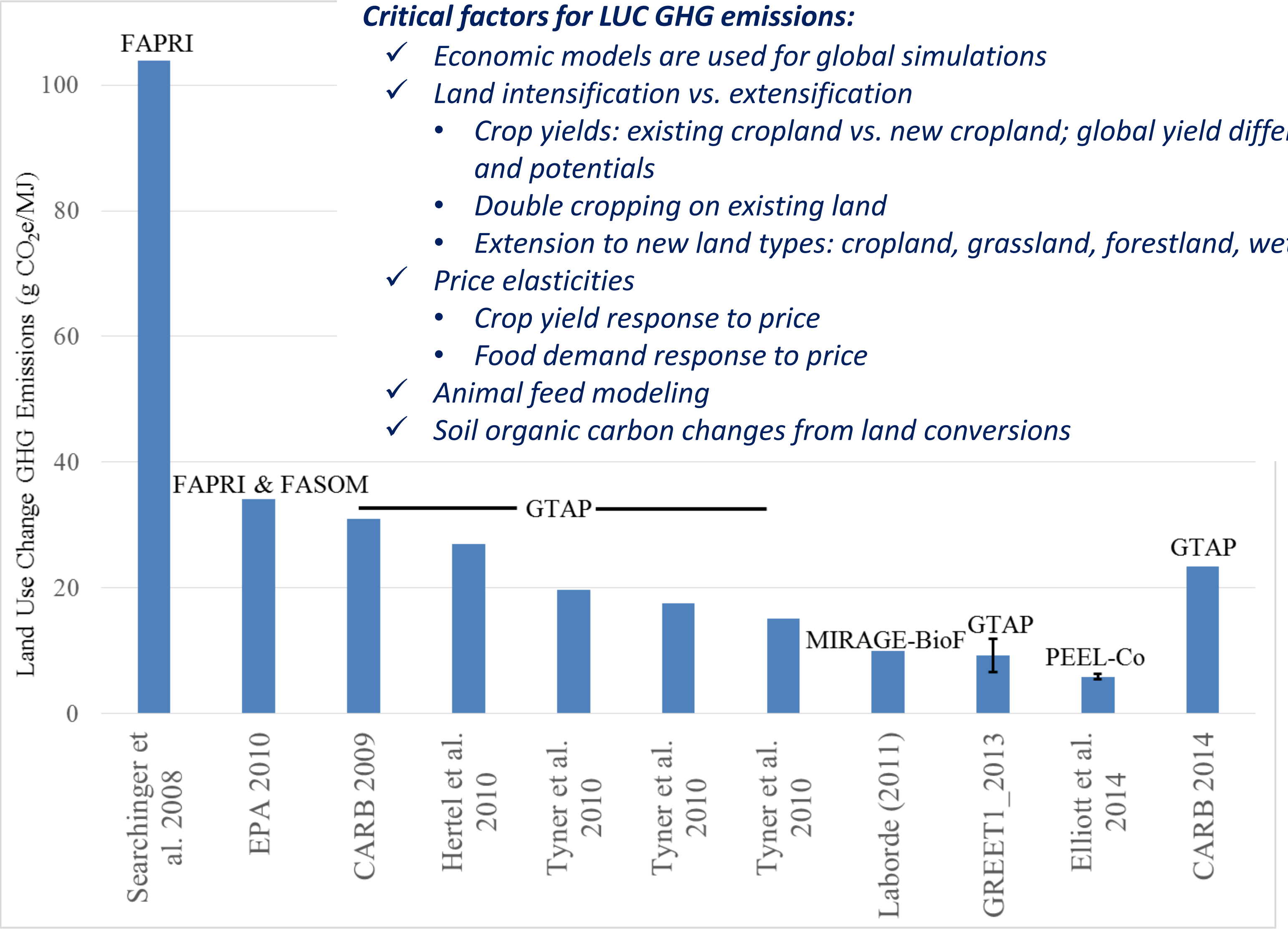


Biofuel production pathways and co-product methods included in this Study.

Biofuel Pathway	Method of Dealing with Multiple Products	Case Number
Corn to ethanol	Displacement	C-E1
	Mass	C-E2
	Energy content	C-E3
	Market value	C-E4
	Process purpose	C-E5
Switchgrass to ethanol	Displacement	G-E1
	Energy content	G-E2
	Market value	G-E3
Soybeans to biodiesel	Displacement	S-BD1
	Mass	S-BD2
	Energy content	S-BD3
	Market value	S-BD4
Soybeans to renewable diesel	Displacement	S-RD1
	Mass	S-RD2
	Energy content	S-RD3
	Market value	S-RD4
	Hybrid allocation	S-RD5



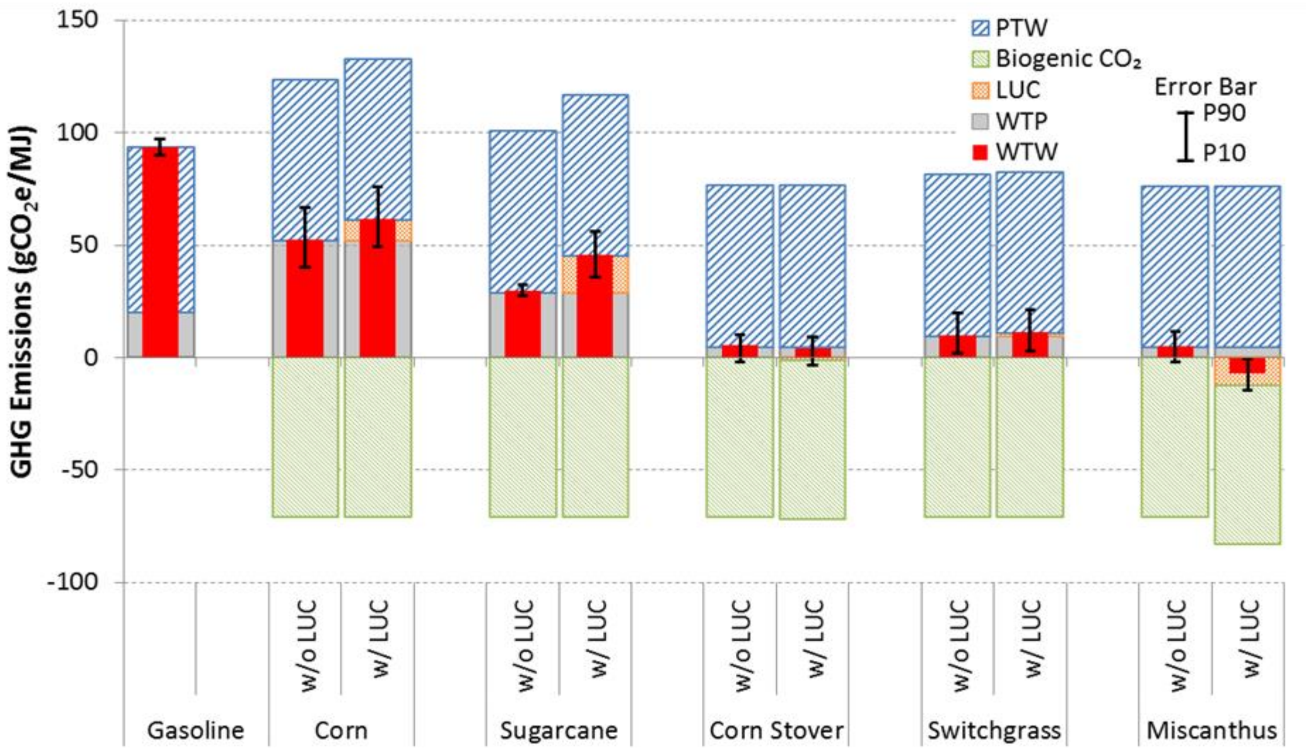
Trend of estimated land-use change GHG emissions for corn-based ethanol

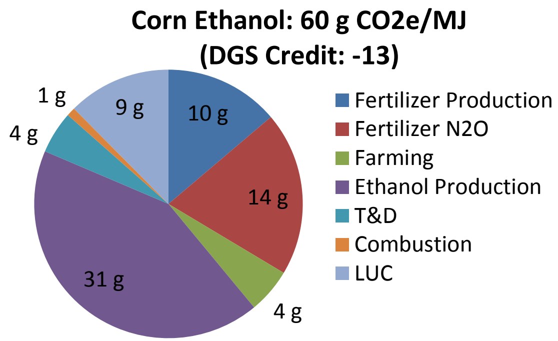


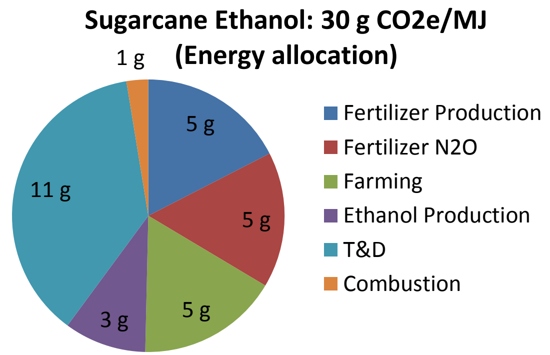
Critical factors for LUC GHG emissions:

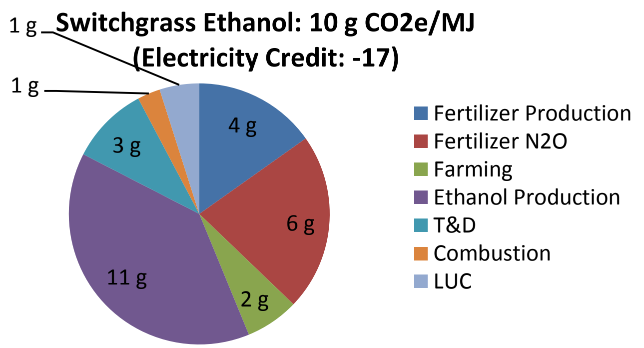
- ✓ *Economic models are used for global simulations*
- ✓ *Land intensification vs. extensification*
  - *Crop yields: existing cropland vs. new cropland; global yield differences and potentials*
  - *Double cropping on existing land*
  - *Extension to new land types: cropland, grassland, forestland, wetland, etc.*
- ✓ *Price elasticities*
  - *Crop yield response to price*
  - *Food demand response to price*
- ✓ *Animal feed modeling*
- ✓ *Soil organic carbon changes from land conversions*

LCA GHG emissions of gasoline and bioethanol pathways









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